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FLIGHT SIMULATOR EXPERIMENTS AND ANALY-
SES IN SUPPORT OF FURTHER DEVELOPMENT
OF MUL-F-83300 V/STOL FLYING QUALITIES
SPECIFICATION

Edward W. Vinje, et al

United Aircraft Research Laboratories

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13. Abstract (Continued) -0.25 to -0.35 are necessary for satisfactory flying qualities with unlimited T/W.

Results for unconventional control techniques evaluated indicate that rotor-propulsion system stored energy can be used to offset limitations in installed control power. Independent thrust-vector control can be used for hovering and maneuvering when properly implemented. Rate-command/attitude-hold control does not appear to provide benefits for hover and low-speed flight.

The exceedance data show that speed-stability and damping are the configuration parameters having the greatest effects on control power usage. Control system lags have little effect on pitch and roll control-moment usage, but they increase yaw control-moment and thrust usage somewhat. The largest amounts of control moment were used for the quick stop task; the smallest amounts were used for hover and turn-over-a-spot. The data indicate that the installed total moment for pitch plus roll control must be sufficient to account for simultaneous usage by the pilot; it cannot be assumed that pilots make independent pitch and roll control inputs.

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**FLIGHT SIMULATOR EXPERIMENTS AND ANALYSES
IN SUPPORT OF FURTHER DEVELOPMENT OF
MIL-F-83300 - V/STOL FLYING QUALITIES SPECIFICATION**

EDWARD W. VINJE

DAVID P. MILLER

Approved for public release; distribution unlimited

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FOREWORD

This report was prepared for the United States Air Force by the United Aircraft Research Laboratories, East Hartford, Connecticut.

The work reported herein was performed by the United Aircraft Research Laboratories under the sponsorship of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The research was conducted under Subcontract S-72-4 to Calspan Corporation (formerly the Cornell Aeronautical Laboratory) as part of Air Force Contract F33615-71-C-1722, Project 643A. The AFFDL project engineer was Mr. Terry Neighbor (AFFDL/FGC) and the Calspan project engineer was Mr. David Key.

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ABSTRACT

Fixed- and moving-base flight simulator experiments and analyses were conducted to provide data for use in substantiating, refining and extending the hovering and low-speed-flight portion of MIL-F-83300 - V/STOL Flying Qualities Specification. For longitudinal and lateral control, the following areas were investigated: turbulence intensity, control lags and delays, control-moment limits, control moments through stored energy, inter-axis motion coupling, independent thrust-vector control and rate-command/attitude-hold control. For height and directional control, the effects of damping levels, control lags and delays, and control power limits were investigated. Opinion ratings, pilot comments, and pilot-selected control sensitivities were recorded in the flight simulator experiments; control-power-usage data were also obtained.

The results indicate that the MIL-F-83300 Level 1 requirement for V/STOL dynamic response provides aircraft dynamics which remain controllable for nominal increases in gust intensity. The specification appears to generally exclude pitch and roll control lags, and lags in thrust response, which cause unsatisfactory flying qualities; it admits lags for which pilot opinion does not deteriorate. However, it also excludes directional control lags which do not degrade opinion. The results further indicate that the specification for installed control moments provides levels which are satisfactory but not excessive. Control sensitivities selected by the pilots also generally fall within the boundaries specified, but are much closer to the lower limit than to the upper. Finally, data from the height control study show that minimum Z_w levels of -0.25 to -0.35 are necessary for satisfactory flying qualities with unlimited T/W.

Results for unconventional control techniques evaluated indicate that rotor-propulsion system stored energy can be used to offset limitations in installed control power. Independent thrust-vector control can be used for hovering and maneuvering when properly implemented. Rate-command/attitude-hold control does not appear to provide benefits for hover and low-speed flight.

The exceedance data show that speed stability and damping are the configuration parameters having the greatest effects on control power usage. Control system lags have little effect on pitch and roll control-moment usage, but they increase yaw control-moment and thrust usage somewhat. The largest amounts of control moment were used for the quick stop task; the smallest amounts were used for hover and turn-over-a-spot. The data indicate that the installed total moment for pitch plus roll control must be sufficient to account for simultaneous usage by the pilot; it cannot be assumed that pilots make independent pitch and roll control inputs.

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SYMBOLS

| | |
|-------------------|---|
| BC1-BC6 | Basic V/STOL aircraft configurations 1 through 6 (see Table I) |
| C_1, C_2, C_3 | Coefficients used in nonlinear representation for control moments available through rotor-propulsion system stored energy (see Eq. (1)) |
| CM_m | Maximum pitch, roll and yaw moments available for control, rad/sec ² |
| CM_{SE} | General notation for control moments available through stored energy, rad/sec ² |
| \overline{CM}_5 | Average pitch, roll and yaw control moments exceeded 5-percent of the time with unlimited moments available, rad/sec ² |
| d_e, d_a | Time delays in pitch and roll response, respectively, to control inputs, sec |
| d_{η} | Time delay in thrust response to collective control input |
| g | Gravitational constant, 32.2 ft/sec ² |
| HOV | Designates hover subtask |
| I_x, I_y, I_z | Moments of inertia in roll, pitch and yaw, slug-ft ² |
| j | $\sqrt{-1}$ |
| L_c | Roll control moment commanded by pilot and SAS divided by I_x , rad/sec ² |
| L_{cm} | Maximum available L_c , rad/sec ² |
| L_{c0} | Reference value of L_c , rad/sec ² |
| \bar{L}_{c0} | Averaged L_{c0} , rad/sec ² |
| L_p | Roll rate damping divided by I_x , per sec |
| L_q | Rolling moment due to pitch rate divided by I_x , per sec |

SYMBOLS (Cont'd)

| | |
|------------------|---|
| L_{vg} | Lateral speed-stability parameter divided by I_x , per sec ³ |
| $L_{\delta a}$ | Lateral control sensitivity divided by I_x , (rad/sec ²)/in. |
| $L_{\delta e}$ | Rolling moment due to longitudinal control stick input, (rad/sec ²)/in. |
| L_{ϕ} | Roll attitude stabilization divided by I_x , per sec ² |
| m | Aircraft mass, slugs |
| MAN | Designates entire maneuvering subtask, i.e., motion in both the x and y directions |
| M_c | Pitch control moment commanded by pilot and SAS divided by I_y , rad/sec ² |
| ΔM_c | Increment to pitch control moment available through rotor-propulsion system stored energy, rad/sec ² |
| M_{cm} | Maximum available M_c , rad/sec ² |
| M_{c0} | Reference value of M_c , rad/sec ² |
| \bar{M}_{c0} | Averaged M_{c0} , rad/sec ² |
| M_{c5} | Pitch control-moment level exceeded 5-percent of the time with unlimited moment available divided by I_y , rad/sec ² |
| $M_{\dot{\phi}}$ | Pitching moment due to roll rate divided by I_y , per sec |
| M_q | Pitch rate damping divided by I_y , per sec |
| \dot{M}_{TS} | Commanded rate-of-change of pitch control moment for thumb switch input, (rad/sec ²)/sec |
| M_{ug} | Longitudinal speed-stability parameter divided by I_y , per sec ³ |
| $M'_{\delta a}$ | Pitching moment due to lateral control stick input, (rad/sec ²)/in. |
| $M_{\delta e}$ | Longitudinal control sensitivity divided by I_y , (rad/sec ²)/in. |

SYMBOLS (Cont'd)

| | |
|--------------------|--|
| M_0 | Pitch attitude stabilization divided by I_y , per sec^2 |
| N_c | Yaw control moment commanded by pilot and SAS divided by I_z , rad/sec^2 |
| N_{c5} | Yaw control-moment level exceeded 5-percent of the time with unlimited moment available divided by I_z , rad/sec^2 |
| N_{cm} | Maximum available N_c , rad/sec^2 |
| N_r | Yaw rate damping divided by I_z , per sec |
| N_v | Yaw-due-to-lateral-velocity parameter divided by I_z , $\text{rad}/(\text{ft-sec})$ |
| $N_{\delta r}$ | Yaw control sensitivity divided by I_z , $(\text{rad/sec}^2)/\text{in.}$ |
| PR | Pilot opinion rating based on Harper-Coller scale |
| APR | Degradation in pilot rating |
| P_{LL} | Percent time commanded roll moment exceeded installed roll control moment, percent |
| P_{ML} | Percent time commanded pitch moment exceeded installed pitch control moment, percent |
| P_{NL} | Percent time commanded yaw moment exceeded installed yaw control moment, percent |
| P_{SL} | Percent time simultaneous pitch and roll moment commands exceeded the sum of the installed pitch and roll control moments, percent |
| P_{TL} | Percent time commanded thrust exceeded installed thrust, percent |
| QS | Designates entire quick-stop subtask, i.e., motion in both x and y directions |
| s | Laplace operator, $1/\text{sec}$ |
| SAS | Stability augmentation system |
| S_{u_g}, S_{v_g} | Power spectrum of longitudinal and lateral turbulence components, respectively, ft^2/sec |

SYMBOLS (Cont'd)

| | |
|--|---|
| $t_{\ddot{\theta}_{\max}}, t_{\ddot{\phi}_{\max}}, t_{\ddot{\psi}_{\max}}$ | Time interval following control input for pitch, roll and yaw, respectively, within which MIL-F-83300 (paragraph 3.2.4, Ref. 1) stipulates that maximum initial angular acceleration shall occur, 0.3 sec |
| TS | Thumb-switch thrust-rotation command, 0 or ± 1 ($+1$ is aft) |
| TU | Designates ± 180 deg turn subtask |
| T/W | Thrust-to-weight ratio |
| $(T/W-1)_5$ | Five-percent incremental T/W usage level, g's |
| $\Delta T/W$ | Increment to thrust-to-weight ratio, g's |
| UL | Notation for effectively unlimited control moment or thrust level |
| U_m | Mean wind from the north (000 deg true), 10 kts |
| x | Conventional longitudinal axis notation in the body-axis system, ft |
| XM | Designates x-direction part of the maneuver subtask |
| XQS | Designates x-direction part of the quick-stop subtask |
| X_u | Longitudinal drag parameter divided by m, per sec |
| y | Conventional lateral-axis notation in the body-axis system, ft |
| YM | Designates y-direction part of the maneuver subtask |
| YQS | Designates y-direction part of the quick-stop subtask |
| Y_{P_h} | Pilot model transfer function for height control loop |
| Y_{P_θ} | Pilot model transfer function for pitch control loop |
| Y_{P_ψ} | Pilot model transfer function for yaw control loop |
| Y_v | Lateral drag parameter divided by m, per sec |
| Z_w | Height velocity damping divided by m, per sec |

SYMBOLS (Cont'd)

| | |
|-----------------------------|---|
| $Z_{W_a}, Z_{W_s}, Z_{W_T}$ | Notation for aerodynamic, stability augmentation system and total Z_W , respectively, per sec |
| Z_{δ_c} | Height control sensitivity divided by m , (ft./sec ²)/in. |
| $\dot{\gamma}$ | Thrust-vector-rotation rate, deg/sec |
| γ_{δ_e} | Thrust-vector angle per inch of control input, deg/in. |
| δ_c | Collective control displacement, in. |
| ζ | Damping ratio of oscillatory roots |
| ζ_a, ζ_e | Damping ratios of second-order lags in roll and pitch response to control inputs, respectively |
| θ | Euler pitch attitude angle, rad |
| σ_{ug} | RMS longitudinal turbulence, ft/sec |
| σ_{vg} | RMS lateral turbulence, ft/sec |
| τ_a, τ_e | Time constant for first-order lag in roll and pitch control response, respectively, sec |
| τ_h | Time constant for first-order lag in thrust response to collective control input, sec |
| τ_{Δ} | Time constant for decay of incremental control power available through stored energy, sec |
| τ_{ψ} | Time constant for first-order lag in yaw response to pedal input, sec |
| ϕ | Euler roll attitude angle, rad |
| ψ | Euler yaw attitude angle, rad |
| ω_d | Damped frequency of the aircraft attitude (pitch or roll) oscillatory roots, rad/sec |
| ω_n | Natural frequency of the aircraft attitude (pitch or roll) oscillatory roots, rad/sec |
| ω_{na}, ω_{ne} | Natural frequencies of second-order lag in roll and pitch response to control inputs, respectively, rad/sec |

SECTION I

INTRODUCTION

A specification for V/STOL aircraft flying qualities, MIL-F-83300, has recently been developed under Air Force sponsorship (Ref. 1). It is based on the results of an extensive evaluation of previous V/STOL flying qualities studies as well as the findings of recent experimental and analytical research funded by the Air Force. Most of the latter was conducted as part of the VTOL Integrated Flight Control System (VIFCS) program. The specification and its supporting documentation provide guidance in the design of V/STOL aircraft control systems as well as a standard for flying qualities. They also are the culmination of research which represents a major advance in the understanding of V/STOL flight characteristics.

Additional research is required, however, in the V/STOL hover and low-speed flight regime. In particular, general information is needed on requirements for installed control power, i.e., control moments and thrust-to-weight ratio. Providing appropriate levels of control power for hover and low-speed flight is a critical part of the design of V/STOL aircraft. Despite its importance, there are little general data available which relate flying qualities to installed control power (Refs. 2 through 4). A related factor which has received almost no attention is the incremental control moment or thrust which can be obtained from rotor-propulsion system stored energy. By temporarily converting a part of the rotor-propulsion system angular momentum to control power, it is possible to supplement the installed control powers. Other general areas which should be investigated further are control lags and delays and inter-axis motion coupling. Motion coupling in particular has not been given adequate attention. Control and rate coupling, for example, exist to some degree in almost all V/STOL aircraft and their effects can lead to a significant degradation in flying qualities. In general, however, the specification treats motion coupling only qualitatively.

An uncertainty also exists over the level of height velocity damping, Z_w , needed for satisfactory height control characteristics. MIL-F-83300 indicates that height control will be satisfactory providing that Z_w is not positive, i.e., not destabilizing. Results which support this contention can be found (Ref. 5), but data which indicate a requirement for a significant level of negative Z_w are also available (Refs. 6 and 7). The height control portion of the specification also assumes that a tradeoff exists between the level of height velocity damping present in the aircraft and the required installed thrust-to-weight ratio. Although there are results which support this assumption, it merits further substantiation. Finally, MIL-F-83300 would be more useful if its scope could be extended to encompass

some unconventional V/STOL control systems. The specifications may already apply to many aspects of hover and low-speed flight with such systems. However, its limitations in this regard are not known and it would be beneficial to examine V/STOL flying qualities with several unconventional systems that might be used on future aircraft. Examples of these types of systems are rate-command/attitude-hold or "stick steering" control and thrust-vector control independent of aircraft attitude.

The study described in this report provides additional information on the hovering and low-speed flying qualities of V/STOL aircraft. The objective of the program was to provide experimental flight simulator data and analyses which will be used to substantiate, refine, and extend the hovering and low-speed flight portion of the V/STOL Flying Qualities Specification.

SECTION II

BACKGROUND OF EXPERIMENTAL PROGRAM

This section contains a description of the studies conducted using the UAC V/STOL Flight Simulator and a discussion of the equipment and procedures used in the experimental program. Most of the equipment and many of the procedures used for the experimental studies were similar to those described in Refs. 7 and 8. Also, the flight simulation for this study was designed to correspond as closely as possible to that implemented at Norair for their previous VIFCS study (Ref. 9). Table A-I is a summary of parameters for cases evaluated and a key to tables in Appendices A, B, C and D that are tabulations of all the data discussed in Sections III through V. Additional details of the flight simulation are contained in Appendix F.

A. Flight Simulator Studies

The experimental program was designed to provide data to substantiate, refine and extend the hovering and low-speed flight portion of the V/STOL Flying Qualities Specification. It included studies of longitudinal and lateral flying qualities, height control and directional control. Emphasis was placed on obtaining information related to requirements for installed control power. The data obtained generally consisted of pilot opinion ratings, pilot-selected control sensitivities and measured control moment and/or thrust usage.

1. Longitudinal and Lateral Control

There were seven different investigations conducted in this part of the program. They were concerned with the effects of (1) turbulence intensity, (2) lags and delays in the response to control inputs, (3) limits on the available control moments, (4) incremental pitch control moment through stored energy, (5) inter-axis motion coupling, (6) thrust-vector control independent of aircraft attitude, and (7) rate-command/attitude-hold control. Six basic V/STOL configurations were selected. A range of values of the parameter being considered was then evaluated for each basic configuration. Also, longitudinal and lateral control were generally evaluated together; only one pilot opinion rating was given for a test case, and this represented the pilot's assessment of the combined longitudinal and lateral flying qualities. In addition, control moments were effectively "unlimited" and pitch, roll and yaw control-moment usage was measured for each study, unless noted otherwise.

a. Basic Configurations

The six basic configurations had conventional rate and attitude stability augmentation, and each was similar to configurations evaluated in the previous Norair and UARL studies (Refs. 7 through 9). They also were symmetrical in that each lateral stability derivative had the same value as the corresponding longitudinal derivative. The directional and vertical stability derivatives were the same for all six configurations. Table I lists their stability derivatives and root locations; roots are also plotted in Fig. 1. It is apparent that the basic configurations span a wide range of dynamic response characteristics. They encompass all three of the levels (1, 2 and 3)* used to characterize aircraft flying qualities in MIL-F-83300, in addition to exhibiting a range of responses to turbulence.

TABLE I

STABILITY DERIVATIVES AND ROOT LOCATIONS FOR UARL BASIC CONFIGURATIONS

| Conf. | Level | Stability Derivatives ^{1,2} | | | | Root Locations | |
|-------|-------|--------------------------------------|-------|---------------|--------------------|----------------|--------------------------------|
| | | $M_{u\dot{g}}$ | X_u | $M_{\dot{q}}$ | $M_{\dot{\theta}}$ | Real Root | $-\zeta\omega_n \pm j\omega_d$ |
| BC1 | 1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | $-0.81 \pm j 1.85$ |
| BC2 | 2 | 1.0 | -0.05 | -1.1 | -2.5 | -0.5 | $-0.30 \pm j 1.47$ |
| BC3 | 3 | 1.0 | -0.05 | -2.0 | 0 | -2.2 | $0.08 \pm j 0.68$ |
| BC4 | 1 | 1.0 | -0.20 | -3.0 | -1.7 | -2.5 | $-0.35 \pm j 0.64$ |
| BC5 | 1 | 0.33 | -0.20 | -1.7 | -4.2 | -0.29 | $-0.81 \pm j 1.85$ |
| BC6 | 2 | 1.0 | -0.20 | -1.1 | -2.5 | -0.65 | $-0.32 \pm j 1.48$ |

1. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivatives.

2. Directional derivatives for all configurations: $N_V = 0.002$, $N_r = -1$, $N_{\dot{r}} = 0.20$; Vertical derivatives: $Z_w = -1$, $Z_{\dot{\theta}_c} = -3.2$, $T/W > 1.15$.

*Level 1 flying qualities are "clearly adequate for the mission"; Level 3 are such that the "aircraft can be controlled safely but pilot workload is excessive or mission effectiveness is inadequate, or both"; and Level 2 flying qualities lie between these extremes.

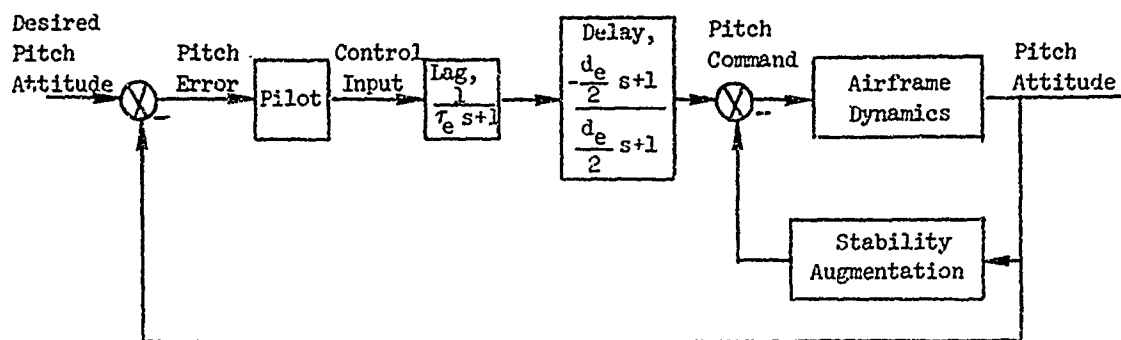
Configurations BC1, BC4 and BC5 are Level 1, but BC4 exhibits a larger attitude response to turbulence ($M_{\dot{u}}g = -L_{\dot{v}}g = 1.0$) than BC1 and BC5 ($M_{\dot{u}}g = -L_{\dot{v}}g = 0.33$). Also, BC4 and BC5 have greater position responses to turbulence than BC1 ($X_{\dot{u}} = Y_{\dot{v}} = -0.20$ versus $X_{\dot{u}} = Y_{\dot{v}} = -0.05$). Configurations BC2 and BC6 are Level 2 with large speed-stability parameters. This feature, combined with the lower levels of damping, results in significant attitude disturbances due to gusts. Configuration BC6 also has the large drag parameters and the attendant large position responses to turbulence. Finally, configuration BC3 is Level 3 with lightly damped dynamics, large speed-stability parameters ($M_{\dot{u}}g = -L_{\dot{v}}g = 1.0$), and large attitude disturbances from turbulence. It is important to note also that all of the rate damping and attitude stabilization represented by these derivatives in Table I (i.e., $M_{\dot{u}}$, $M_{\dot{\theta}}$ and their lateral, vertical and directional counterparts) was assumed to be provided by a stability augmentation system (SAS).

b. Turbulence Intensity

This study was conducted to provide information on the sensitivity of aircraft with different level flying qualities to changes in turbulence intensity and to obtain control-moment usage data. The flying qualities of Level 1 aircraft should be somewhat insensitive to gust level. That is, the MIL-F-83300 definition for V/STOL Level 1 dynamic response must be formulated such that flying qualities remain acceptable for commonly encountered turbulence intensities. Greater deterioration in flying qualities would be expected for Level 2 and 3 aircraft. Each of the six basic configurations was evaluated at three levels of rms longitudinal and lateral turbulence intensity, $\sigma_{u_g} = \sigma_{v_g} = 3.4, 5.8$ and 8.2 ft/sec. The wind simulation also included a mean wind $U_m = 10$ kt (≈ 17 ft/sec) from the north. Note that only for this study were rms turbulence intensities other than $\sigma_{u_g} = \sigma_{v_g} = 3.4$ ft/sec evaluated. For the rest of the program the wind simulation consisted of $\sigma_{u_g} = \sigma_{v_g} = 3.4$ ft/sec and $U_m = 10$ kt. Details of the wind simulation are described in Section II.B.1.

c. Lags and Delays in Attitude Response to Control Inputs

Pitch and roll control lags and delays were evaluated to test the adequacy of the MIL-F-83300 specification for such effects (paragraph 3.2.4, Ref. 1). These lags and delays only operated on the pilot's control stick inputs, i.e., the stability augmentation system (SAS) commands were not affected. The location of the lags and delays in the pitch attitude control loop is shown schematically in Sketch II-A. The implementation was identical for the roll loop. In the specification pitch, roll or yaw lags and delays are presumed to be within acceptable limits if the time to reach the initial maximum angular acceleration is no greater than 0.3 sec. To span this requirement with both acceptable and unacceptable values, first-order lags having time constants of 0.1, 0.3 and 0.6 sec were evaluated for each basic configuration. Also, the longitudinal and lateral lags were always



SKETCH II-A. Location of Lags and/or Delays Simulated in Pitch Response to Control Inputs

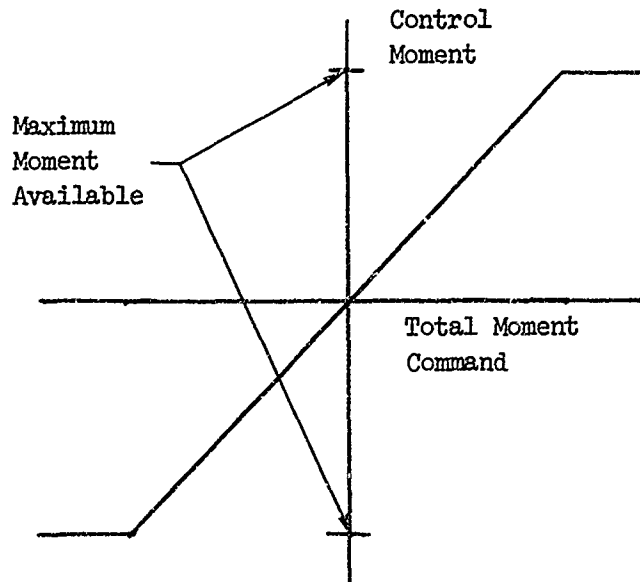
equal ($\tau_e = \tau_a$) for a given test case. In addition, pitch and roll moment delays, $d_e = d_a$, of 0.1 sec were evaluated with and without a combined first-order lag of $\tau_e = \tau_a = 0.3$ sec. Configurations BC1 and BC2 were used for these test cases. The effects of second-order control lags were also investigated with configuration BC1 to further test the specification. The significance of amplitude versus phase effects was examined by varying the damping ratio and natural frequency of the second-order lags.

d. Limits on Available Control Moments

The purpose of the control-moment-limit study was to investigate the effects of aircraft configuration and control system parameters on the total control moments (i.e., moments commanded by the pilot and the rate damping and attitude stabilization derivatives or SAS) necessary for pilot acceptance. Another objective was to examine whether these required installed control moments correlate with the control moment levels exceeded some given small percent of the time with unlimited moment available, e.g., the 5-percent level. Information on the adequacy of the MIL-F-83300 specification for pitch, roll and yaw control power (paragraph 3.2.3.1) was also provided by comparing it with the results of this study.

Configurations BC1, BC4, BC5 and BC6 were considered initially without control lags or delays. Three to five levels of available total control moment were evaluated for each configuration, and pilot opinion ratings were used to indicate the sufficiency of the levels. Pilots were not aware of the control-moment limits except as they affected flying qualities. The moment limits were applied on an analog computer, not to the physical control stick motion and the maximum control travels available were such that the limits would always be exceeded if the maximum travels were used. The control moment versus moment command characteristics simulated in the moment

limit study for pitch, roll and yaw control are shown in Sketch II-B. Note that the moments available in the pitch, roll or yaw axes were never identical. The reference limits or starting points for the installed control-moment levels (pitch, roll and yaw) were averages of those levels exceeded 5 percent of the time (CM_5) with unlimited moment available. The limits for the remaining test cases were developed by increasing (or decreasing) the reference levels by integral multiples of 10 percent.



SKETCH II-B. Pitch, Roll or Yaw Control Moment Versus Total Control-Moment Command Characteristics for the Moment Limit Study

The effects of control-moment limits were next evaluated with control system lags and delays present. Configurations BC1 and BC5 were used with pitch and roll response delays of $d_e = d_a = 0.1$ sec in combination with first-order lags of either $\tau_e = \tau_a = 0.3$ sec or 0.6 sec. The moment limits evaluated and the procedures for this investigation were unchanged from those for no control lags or delays.

e. Control Moments Through Stored Energy

Several types of V/STOL aircraft derive pitch and roll control moments from cyclic and/or collective changes of rotor system blade angles. Momentary incremental control moments above the installed moment levels can be obtained for such systems by abruptly increasing blade angles to values larger than the normal operating limit. Of course, the aircraft's powerplant will be unable to maintain engine rpm at this large blade angle, and rpm will decay. However, the brief increase in moment may be sufficient

to compensate for deficiencies in the installed control moments. This study was undertaken to examine whether the stored energy in typical V/STOL rotor-propulsion systems could be used to such advantage.

Preliminary analyses indicate that it may be possible to approximate the control moments available from stored energy, CM_{SE} , by

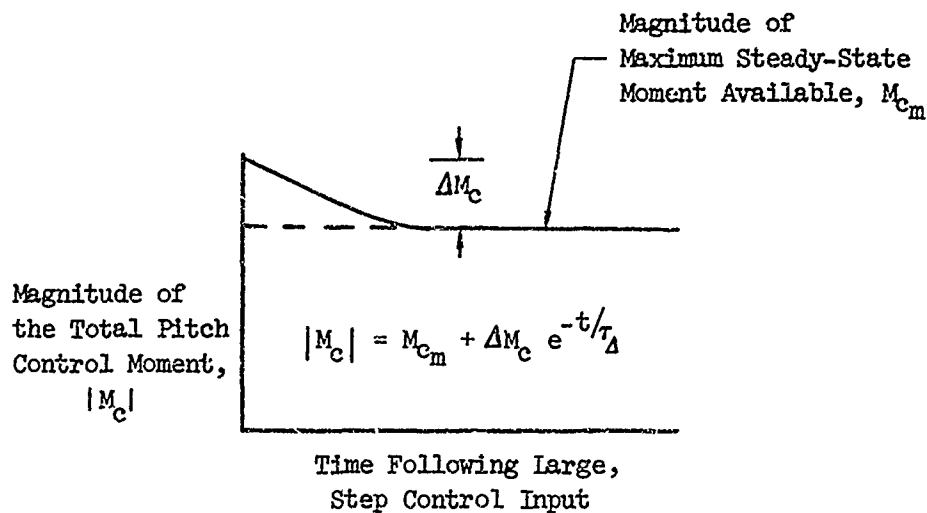
$$\frac{d(rpm)}{dt} + C_1 (rpm)^2 = C_2 \quad (1)$$

$$CM_{SE} = C_3 (rpm)^2$$

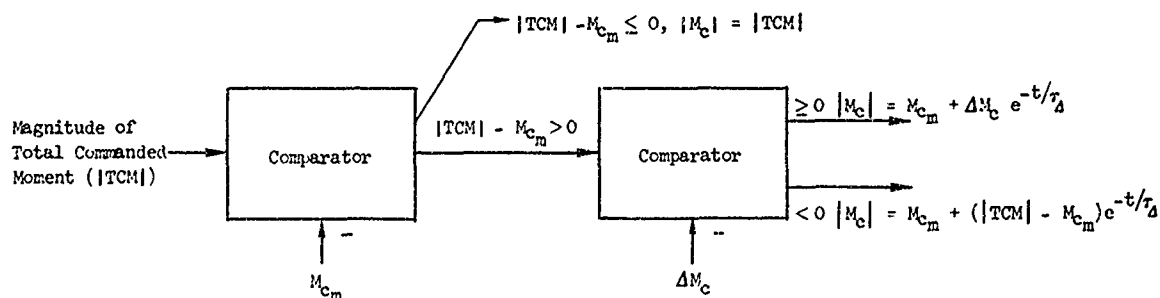
where coefficient C_1 is related to the blade drag, C_2 to the available engine horsepower, and C_3 to the blade lift coefficient. Also, coefficients C_1 and C_3 both change when the pilot moves his control stick. For this study, stored energy effects were simulated for pitch control moments only and a linearized version of Eq. (1) was used to represent stored energy (Eq. (2)).

$$\tau_A \frac{d}{dt} (CM_{SE}) + CM_{SE} = \tau_A \frac{d}{dt} (|\text{Commanded Moment}| - M_{C_m}) \quad (2)$$

In Eq. (2) the parameter τ_A is the time constant associated with the stored energy decay and M_{C_m} is the steady-state or installed control moment. Also, the maximum control moment increment available from stored energy is defined as ΔM_C and the function $(|\text{Commanded Moment}| - M_{C_m})$ in Eq. (2) cannot be larger than ΔM_C . In addition, the stored energy increment was available for both positive and negative control commands as indicated in Eq. (2). The pitch control-moment step response for the stored energy study is shown in Sketch II-C. The moment response shown there is similar to the maximum pitch control moment the pilot and/or SAS could command if a large, rapid control input was made and sustained. The total moment available, then, consisted of a continuously available installed moment, M_{C_m} , plus a transient term which was excited if the magnitude of the total command exceeded M_{C_m} . The transient gave an abrupt increase related to the $|\text{Commanded Moment}| - M_{C_m}$ (up to the maximum increment of ΔM_C) that decayed with time constant τ_A . M_{C_m} and ΔM_C are considered to be positive functions in this discussion. The increment from stored energy could be used at any time, but after it decayed the pilot (and/or SAS) had to reduce the commanded moment and wait until the stored energy simulation recovered (the recovery time constant was also τ_A). This effectively simulated the time it would take a propulsion system to restore rotor rpm. A logic diagram illustrating the stored-energy simulation is shown in Sketch II-D. Representative values for the increment and the rpm decay (and recovery) time were determined from an analysis of the XC-142



SKETCH II-C. Step-Response Characteristics of the Simulation of Incremental Control Moment Available Through Stored Energy



SKETCH II-D. Schematic Showing Switching Logic for Stored Energy Simulation

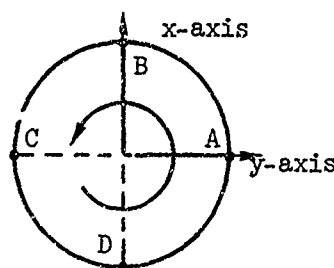
propulsion system. It appears that a moment increment of 30 percent of the installed moment is possible with associated decay time constants of $\tau_d = 0.05$ and 0.10 sec. Values for τ_d of as much as 0.2 sec may be possible for helicopters because of the greater rotor-system inertia.

The effects on flying qualities of pitching moment available through stored energy were investigated with the same basic configurations considered in the control-moment limit study, i.e., BC1, BC4, BC5 and BC6. The installed pitch control moment, M_{cm} , for each configuration was set at a low level

which yielded unsatisfactory pilot ratings without stored energy effects. All other installed control moments were set at satisfactory levels. The effects of the incremental pitch control moments supplied by stored energy were then evaluated for different combinations of ΔM_c and τ_d . Pilot ratings were used to assess the effects of stored energy. As for the study of control-moment limits, the pilots were not aware of the limits on pitch control power except through aircraft flying qualities. Control-moment data were not measured during the stored energy investigation.

f. Inter-Axis Motion Coupling

This study was performed to determine acceptable values of attitude rate coupling (M_p and L_q) and control coupling (M_{δ_a} and L_{δ_e}). An analysis was conducted initially to determine appropriate polarities and magnitudes for these parameters. The sign convention used for the attitude rate coupling (M_p positive and L_q negative) was derived from a simple analysis of hingeless-rotor aerodynamics. When the rotor tip-path-plane shown in Sketch II-E



SKETCH II-E. Top View of Rotor Tip Path Plane

undergoes pitch rates, one effect gives rise to net rolling moments. For example, if pitch attitude is increased by a positive pitch rate, the angle of attack of a blade in arc DAB will also increase, while that in arc BCD will decrease, causing a negative rolling moment (L_q negative). Similarly, a positive roll rate (increase in roll attitude) results in a positive pitching moment (M_p positive). Data in Ref. 10 indicate that rate coupling levels ranging from $M_p = 0.3$, $L_q = -2.7$ to $M_p = 1.5$, $L_q = -14$ can be present in uncompensated helicopter control systems, depending on rotor design.

The sign convention for control coupling can also be interpreted by reference to Sketch II-E. The maximum control moment for an articulated (hinged) rotor occurs when the blade has moved an additional 90 deg after a blade-angle (cyclic) change, i.e., the maximum pitching moment occurs at point B if the blade angle is changed at A. For a hingeless rotor the

maximum moment occurs after a smaller phase lag, e.g., somewhere in the arc AB for a blade angle change at A. Therefore, a positive pitch control input gives rise to a negative roll moment ($L_{\delta e} < 0$) and a positive roll control command results in a positive pitch moment ($M_{\delta a} > 0$). It should be noted that, with the sign conventions described, the effects of attitude rate and control coupling are additive. For example, a positive pitch control input yields a positive pitch rate and, since both L_q and $L_{\delta e}$ are negative, the induced rolling moments from both sources are negative. However, in the flight simulator evaluation of coupling effects, coefficients having signs which resulted in cancelling moments ($L_q < 0$, $L_{\delta e} > 0$ and $M_p > 0$, $M_{\delta a} < 0$) were also evaluated.

Configurations BC1 and BC2 were considered in this study with rate coupling levels of $M_p = -L_q = 2$ and 4 and control coupling up to $M_{\delta a}/L_{\delta a} = L_{\delta e}/M_{\delta e} = 0.50$. The different types of coupling were evaluated separately and in combination.

g. Thrust-Vector Control Independent of Aircraft Attitude

Independent thrust-vector control (ITVC) enables the pilot to maneuver aircraft having large drag parameters without large attitude changes. Also, with ITVC, large aircraft can be maneuvered near the ground with a reduced probability of tail strikes (and wing strikes, if lateral ITVC is also available). Only longitudinal ITVC was investigated in this study and it was implemented in two ways. In the first approach the longitudinal thrust vector was rotated using a thumb switch which commanded a constant rate of rotation. Pitch attitude was controlled using the conventional control stick. This technique for thrust-vector control was identical to the implementation of the wing tilt (or thrust-vector) control which was used by the evaluation pilots to trim the effects of mean wind acting through the longitudinal drag parameter. The wing tilt capability was available for all test cases evaluated in the UARL study. However, only for the ITVC study was the pilot permitted to use this device for general position control. The second method of implementation involved proportional control of the thrust-vector angle using the control stick while pitch attitude was controlled with the thumb switch. The thumb switch commanded a fixed rate-of-change of pitching moment (\dot{M}_{TS}). In general, the thrust-vector angle was displayed on the contact analog display with a symbol that moved vertically. Thrust-vector angle was also displayed on the instrument panel. For some of the experiments only the instrument panel display was used. Two Level 1 configurations (BC1 and BC4) and a Level 2 configuration (BC2) were used in the ITVC study. These configurations provide a range of position response characteristics with which to test ITVC. Configurations BC1 and BC2 have low drag parameters ($X_u = Y_v = -0.05$) and, consequently, low position stability and low position response to turbulence. Configuration BC4 has large drag parameters which give it greater position stability but also larger gust-induced position disturbances. Attitude control moments were unlimited for this

study and the thrust-vector angle could be rotated through ± 90 deg. Pitch and roll control-moment usage and thrust-vector angle were measured in the ITVC study.

h. Rate-Command/Attitude-Hold Control

The rate-command/attitude-hold or "stick steering" control system has two significant attributes. First, it will hold trim attitudes while allowing the pilot to center the stick and, second, it provides a rate-command control response for higher frequency control motions. A representative attitude transfer function (pitch) for such a system is given by Eq. (3):

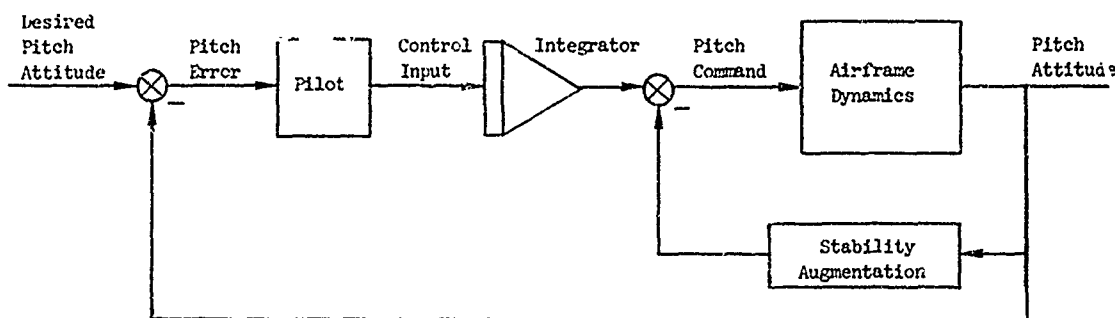
$$\frac{\theta}{\delta_e}(s) = \frac{M_{\delta_e}}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (3)$$

This transfer function can be obtained for a rate and attitude stabilized V/STOL aircraft by integrating the control stick input to the attitude control system. This is the feature which enables the pilot to hold trim attitude with no steady-state control input. The attitude stabilization must then be increased to values which drive the real root of the attitude dynamics, i.e., the real root of the hovering cubic, towards zero, where it will be cancelled by the first-order zero related to drag parameter. If the natural frequency of the quadratic term in Eq. (3) is then sufficiently large, the transfer function θ/δ_e at and below the pilot's crossover frequency ($\omega_c \approx 2.5$ to 3.5 rad/sec, Ref. 8) will effectively be

$$\frac{\theta}{\delta_e}(s) \approx M_{\delta_e}/s \quad (4)$$

However, the dynamics still retain the attitude stabilization features. The lead compensation that must be supplied by the pilot for pitch and roll control and, consequently, the longitudinal flying qualities of this control system, are very dependent on the damping ratio, ζ , and natural frequency, ω_n , of the quadratic in Eq. (3). The rate-command/attitude-hold control system for pitch attitude (and also roll) was implemented as shown in Sketch II-F for this study.

For this study the basic longitudinal and lateral airframe derivatives of configurations BCl and BC4 were used as a base and the rate damping (M_q , L_p) and attitude stabilization (M_θ , L_ϕ) parameters were varied to provide a broad range of ζ and ω_n for the pitch and roll dynamics. The initial parameters chosen were based on a closed-loop analysis of the pilot-aircraft dynamics. Values for ζ and ω_n that could not be obtained with simple



SKETCH II-F. Implementation of Rate-Command/Attitude-Hold Control

attitude and rate feedbacks were not evaluated in this study. Again, the pitch and roll attitude dynamics were identical for each test case.

2. Height Control

The height control program consisted of four studies. They were concerned with the effects on flying qualities of (1) height velocity damping, Z_w , with effectively unlimited thrust, (2) the interaction between Z_w and the installed thrust level, (3) thrust lags and delays, and (4) thrust available through stored energy. The longitudinal, lateral and directional characteristics were defined by the basic configurations and are shown in Table A-I. Pitch, roll and yaw control moments were effectively unlimited. The data obtained consisted of pilot ratings, pilot-selected collective control sensitivities and thrust usage. The measured thrust usage was made up of that which the pilot attempted to command, $Z_{\delta_c} \cdot \delta_c$, and that actually commanded, $Z_{\delta_c} \cdot \delta_c + Z_{w_s} \cdot w$, where Z_{w_s} is the height damping resulting from stability augmentation.

a. Effects of Height Velocity Damping with Unlimited Thrust

This study was undertaken primarily to provide more information on the minimum acceptable level of height velocity damping, Z_w . The MIL-F-83300 specification (paragraph 3.2.5.4) assumes that Level 1 flying qualities for height control can exist for $Z_w = 0$ provided sufficient thrust is available ($T/W > 1.10$). A previous UARL study (Ref. 7) contains data which indicate that a level of $Z_w \approx -0.5$ is necessary for satisfactory height control. A secondary objective of the study was to measure thrust usage data with effectively unlimited thrust-to-weight ratio ($T/W > 1.15$). Levels of total height damping, Z_{wT} , ranging from 0 to -0.8 were evaluated with configurations BCl and BC4. The total damping was assumed to consist of equal aerodynamic, Z_{w_a} , and stability augmentation system (SAS), Z_{w_s} , components.

b. Interaction Between Z_{WT} and Installed Thrust Level

The height control power portion of MIL-F-83300 (paragraph 3.2.5.1) is based on the premise that increased height velocity damping reduces the necessary installed thrust. The study described here was conducted to provide more information on this effect. Height control was evaluated with configuration BCl for six or more levels of Z_{WT} , ranging from -0.1 to -0.5, at each of three installed thrust-to-weight ratios ($T/W = 1.02, 1.05, 1.10$). The T/W ratios considered are pertinent to the definition of level boundaries for the height control power specification. Generally Z_{WT} was composed of equal parts of aerodynamic, Z_{WA} , and SAS, Z_{WS} , damping. However, the effects of all Z_{WA} or all Z_{WS} were also investigated.

c. Thrust Lags and Delays

This investigation was designed to test the specification for thrust magnitude control lags (paragraph 3.2.5.2). First-order lags which result in height control response that spans the Level 1 and 2 requirements ($\tau_h = 0.3$ and 0.6) were evaluated with and without 0.1-sec delays. These lags and delays affected both the control and SAS thrust commands. Configuration BCl was used and several values of Z_{WT} , composed of equal Z_{WA} and Z_{WS} components, were simulated for each combination of control lag and delay. Also, the installed T/W was limited to 1.05 for this study.

d. Thrust Available Through Stored Energy

The effects of incremental thrust from rotor-propulsion system stored energy were investigated using configuration BCl with height control characteristics that were unsatisfactory without stored energy ($Z_{WT} = Z_{WS} = -0.35$, $T/W = 1.02$). Two levels of incremental T/W representing momentary thrust increases of approximately 15 percent and 30 percent, i.e., $\Delta T/W = 0.13$ and 0.28 , were evaluated with decay time constants of $\tau_A = 0.05, 0.1$ and 0.2 sec. Stored energy was simulated as described for pitch control in Section II.A.1.e.

3. Directional Control

The three directional control studies investigated (1) the effects of damping on flying qualities and control-moment usage, (2) control lags and delays, and (3) limits on the available control moment. Two of the basic configurations (BC1 and BC2) were used to represent V/STOL longitudinal and lateral control characteristics. The height-control parameters for the directional studies were as shown in Table A-I. Pitch and roll control moments and thrust-to-weight ratio were effectively unlimited. Yaw control moments were also unlimited unless noted otherwise. Pilot ratings, pilot-selected directional control sensitivities and pitch, roll and yaw control-moment usage were recorded.

a. Effects of Yaw Rate Damping

This study was conducted to provide additional information on the relationship between yaw rate damping and flying qualities and to obtain control-moment-usage data. Yaw rate damping values which spanned the Level 1, 2 and 3 specifications (paragraph 3.2.2.2), for directional damping ($N_r = -1, -0.5$ and 0 , respectively) were evaluated for basic configurations BC1 and BC2. For all test cases N_y was 0.005 .

b. Control Lags and Delays

The effects of directional control lags and delays were also investigated to provide results with which to test the control-lag specification (paragraph 3.2.4). First-order control lags (which affected the pedal response only) with time constants $\tau_\psi = 0.3$ and 0.6 were evaluated with and without 0.1 -sec delays in control response. These lag and delay combinations were each evaluated at N_r levels of -0.5 and -1 . Only configuration BC1 was used in this study and N_y remained 0.005 .

c. Yaw Control-Moment Limits

The levels of yaw control moment necessary for satisfactory directional control were determined (1) to provide comparative results for the MIL-F-83300 control power requirement (paragraph 3.2.3.1) and (2) to evaluate the hypothesis that acceptable moment limits correlate with a level exceeded some small percent of the time for unlimited available moments. Configuration BC1 was again used in this study and N_y remained 0.005 . The yaw control-moment limits considered were $N_{cm} = 0.10, 0.13$ and 0.16 and the effects of these limits were evaluated for two values of N_r , -0.5 and -1.0 . The smallest limit considered, $N_{cm} = 0.10$, was based on yaw control-moment data measured in the turbulence study (Section II.A.1.b). It was the average level exceeded 5 percent of the time for the 3.4 ft/sec rms turbulence intensity.

B. Description of Simulation

1. Simulation of V/STOL Aircraft and Winds

The six-degree-of-freedom equations of motion for hovering and low-speed flight were programmed on an analog computer. They were written using a body-axis coordinate system and were linearized assuming small perturbations from hovering flight (Eq. (F-1), Appendix F; Refs. 7 and 8). Also, the angular momentum effects of such spinning masses as propellers and jet engine rotors were not considered. Products of inertia have also been assumed to be negligible and, with the exception of N_y , derivatives which couple motion between axes were generally disregarded. Pitch and roll rate coupling and control coupling were examined in one of the longitudinal and lateral control studies, however. The wind simulation consisted of a 10 kt (≈ 17 ft/sec)

mean wind from the north (000 deg true), U_m , and turbulence which was introduced along the aircraft x and y body axes. Turbulence was simulated by passing the output of a random noise generator, which had a relatively uniform low-frequency power spectral distribution, through a first-order filter with a break frequency of 0.314 rad/sec (Refs. 7 and 8). The simulated turbulence then excited aircraft rotational and translational motion through the aircraft speed-stability and drag parameters and the yaw-due-to-lateral-velocity parameter (see Eq. (F-1), Appendix F). The turbulence intensity was always equal in the x and y axes, and, in general, an rms level of $\sigma_{u_g} = \sigma_{v_g} = 3.4$ ft/sec was used. With this turbulence intensity, the wind simulation was the same as that used for much of the previous Norair study conducted under the VIFCS program (Ref. 9). Turbulence intensity levels of $\sigma_{u_g} = \sigma_{v_g} = 5.8$ and 8.2 ft/sec were also considered in the study of turbulence effects.

2. Flight Simulation and Display

Fixed- and moving-base VFR flight simulations were used. For any given study, the moving-base simulations were used to check selected fixed-base data which had been previously obtained. Generally, about half the test cases in a particular study were evaluated in the moving-base mode. The same flight simulator used in the previous UARL VIFCS studies (Refs. 7 and 8) was also used for this program. A motion platform has been added to the device, however (Fig. 2).

The simulator consists of a fully enclosed, two-place Sikorsky S-61 cockpit with a conventional instrument panel, a contact analog display for VFR flight simulation, and the six-degree-of-freedom motion platform. The control system for this simulation was made up of standard helicopter flight controls plus a thumb-switch device which could be used to change the longitudinal thrust-vector angle (or wing-tilt angle) and thereby trim the effects of the mean wind acting through the longitudinal drag parameter. The display (Fig. 3) is composed of a ground grid, horizon line, clouded sky and display symbols. Attitude and coarse position information are obtained from the motion of the ground grid, horizon and sky relative to a cross symbol which represents the nose of the aircraft. The cross may either be the electronic symbol shown in Fig. 3 or simply a marker physically attached to the screen surface. For the independent thrust-vector control and height control studies, the latter method was used and the electronic cross was moved to the right side of the screen to indicate thrust-vector angle and altitude, respectively. Precise aircraft position and velocity information are obtained from the motion of the square symbol which indicates a spot on the ground. At the reference hovering altitude of 40 ft, the dimensions of the contact analog screen represented a hover pad approximately 130 ft (longitudinally) by 150 ft and the square symbol an area about 9 ft on a side.

Simulator motion is provided by coordinated movement of the six hydraulic actuators on which the cockpit is mounted (Fig. 2). The stroke position of each actuator, commanded in response to the simulation equations of motion, is generally computed using hard-wired analog circuitry. A PDP-8 digital computer is used to set control modes of the motion platform and to monitor system performance. The simulator motion capabilities are summarized in Table II. The amplitude of the motion-platform frequency response is flat to beyond 1 Hz for each type of angular (e.g., pitch, roll or yaw) or linear motion. The phase lag for each type of motion is approximately 30 deg at 1 Hz.

TABLE II

FLIGHT SIMULATOR ANGULAR AND LINEAR MOTION LIMITS

| Axis | Angular Motion | | | Axis | Linear Motion | | |
|-------|----------------|---------------|------------------------------------|--------------|---------------|------------------|-------------------|
| | Attitude, deg | Rate, rad/sec | Acceleration, rad/sec ² | | Position, ft | Velocity, ft/sec | Acceleration, g's |
| Pitch | ±45 | ±1 | ±1 | Longitudinal | ±5 | ±6 | ±0.5 |
| Roll | ±30 | ±1 | ±1 | Lateral | ±5 | ±6 | ±0.5 |
| Yaw | ±45 | ±1 | ±1 | Vertical | ±2.5 | ±6 | ±1.0 |

The platform's motion limits are too small to permit duplication of all low-frequency aircraft motion commanded by the pilot, especially the linear displacements. Consequently, a "washout" logic has been developed to selectively attenuate motion commands which would cause the simulator to exceed its limits (Appendix F; Ref. 11). This system is based on measured frequency response characteristics of the human's vestibular system. It also orients the cockpit relative to the earth's gravity field to simulate low-frequency aircraft linear accelerations which otherwise could not be represented. Several pilots have evaluated the motion system with this washout logic for hovering and low-speed flight and have generally found that it provides a realistic representation of actual flight.

3. Simulated Flight Task

The flight task performed during the longitudinal and lateral and the directional control studies consisted of the following subtasks: vertical

takeoff and climb to a 40-ft hovering altitude, low-speed maneuvers (air taxi; MAN, XM, YM), quick stops (QS, XQS, YQS), turns-over-a-spot (TU), hover (HOV), and landing. The air-taxi maneuvers were conducted in both longitudinal and lateral directions through simulated distances of ± 65 ft and ± 75 ft, respectively. The pilots followed a cross pattern while holding heading constant (at 000 deg true) and hovered momentarily at the cardinal points of the cross. Airspeeds were generally less than 20 ft/sec during the maneuver task. The pilots next performed the longitudinal and lateral quick stops while also holding heading at 000 deg true. Airspeeds were somewhat larger for the quick stops, and, of course, the aircraft's velocities were arrested more abruptly than for the air-taxi maneuvers. The pilots next performed ± 180 deg turns while maintaining hover position and this was followed by a 60-sec precision hover at the center of the simulated hover pad. The pilots then landed the aircraft.

The turn-over-a-spot subtask was deleted for the height control study and a landing sequence (LS) subtask was performed after the hover. The landing sequence consisted of relatively rapid changes in hovering altitude from 40 ft to 20 ft and back to 40 ft. This was followed by a vertical landing.

4. Pilots

The two UARL evaluation pilots were the same pilots A and B who participated in the previous VIFCS studies conducted at UARL (Refs. 7 and 8). Both are licensed private pilots who have flown a variety of fixed-wing aircraft and one has had limited helicopter experience. They also have each accumulated several hundred hours evaluation time on the flight simulator. For each study in this program pilot B generally evaluated all the fixed-base test cases and pilot A approximately half of them. These ratios were reversed for the height control studies, however. Only pilot B performed moving-base evaluations.

Two Calspan test pilots also participated at different times in the UARL program. Each has extensive experience in both helicopters and V/STOL aircraft. Eleven moving-base simulator shifts of at least 4 hours duration each were set aside for Calspan use. Results from the Calspan evaluations are shown only for Calspan pilot B in this report.

5. Comparative Results from UARL and Norair Simulations

The UARL flight simulation was designed to correspond with that used by Norair in their previous VIFCS program (Ref. 9) and thereby provide comparable results. An indication of the success of this effort can be obtained by comparing pilot ratings for similar test cases from the two simulations. Comparable longitudinal and lateral control rating data for the six UARL basic configurations are shown in Fig. 4 and Table III. The UARL fixed-base

TABLE III

COMPARISON OF PILOT RATINGS FROM NORAIR AND CURRENT UARL STUDY

Wind Simulation: $U_m = 10$ kts, $\sigma_{u_g} = \sigma_{v_g} = 3.4$ ft/sec for Both Simulations

| Basic Conf. | Simulation Case | Longitudinal Stability Derivatives | | | | Lateral Stability Derivatives | | | | PR | |
|-------------|-----------------|------------------------------------|-------|-------|------------|-------------------------------|-------|-------|----------|------|-----|
| | | M_{u_g} | X_u | M_q | M_θ | L_{v_g} | Y_v | L_p | L_ϕ | FB | MB |
| BC1 | UARL T1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.33 | -0.05 | -1.7 | -4.2 | 2 | 2 |
| | NORAIR 308 | 0.33 | -0.05 | -1.7 | -4.2 | -0.33 | -0.05 | -1.7 | -4.2 | | 3.2 |
| BC2 | UARL T10 | 1.0 | -0.05 | -1.1 | -2.5 | -1.0 | -0.05 | -1.1 | -2.5 | 4.5 | 5 |
| | NORAIR 102 | 1.0 | -0.05 | -1.1 | -2.5 | -0.16 | -0.10 | -5.0 | 0 | | 4.5 |
| BC3 | UARL T16 | 1.0 | -0.05 | -2.0 | 0 | -1.0 | -0.05 | -2.0 | 0 | 5 | 6 |
| | NORAIR 117 | 1.0 | -0.05 | -2.0 | 0 | -0.16 | -0.10 | -5.0 | 0 | | 5 |
| BC4 | UARL T7 | 1.0 | -0.20 | -3.0 | -1.7 | -1.0 | -0.20 | -3.0 | -1.7 | 3.5 | 3 |
| | NORAIR 147 | 1.0 | -0.20 | -3.0 | -1.7 | -0.16 | -0.10 | -5.0 | 0 | | 4 |
| BC5 | UARL T4 | 0.33 | -0.20 | -1.7 | -4.2 | -0.33 | -0.20 | -1.7 | -4.2 | 3.5 | 2 |
| | NORAIR 334 | 0.33 | -0.20 | -2.1 | -3.8 | -0.33 | -0.20 | -2.1 | -3.8 | | 3 |
| BC6 | UARL T13 | 1.0 | -0.20 | -1.1 | -2.5 | -1.0 | -0.20 | -1.1 | -2.5 | 4.75 | 6 |
| | NORAIR 141 | 1.0 | -0.20 | -1.4 | -1.7 | -0.16 | -0.10 | -5.0 | 0 | | 6.2 |

data are averaged over two pilots and the moving-base results are for pilot B only. The Norair ratings for each case have been averaged over several pilots. In general, the ratings from the two programs agree relatively well, generally differing by only about one unit or less. Note, however, that only for configuration BCl were the Norair and UARL test cases completely identical. The comparable longitudinal stability derivatives were always quite similar but the lateral derivatives were generally not.

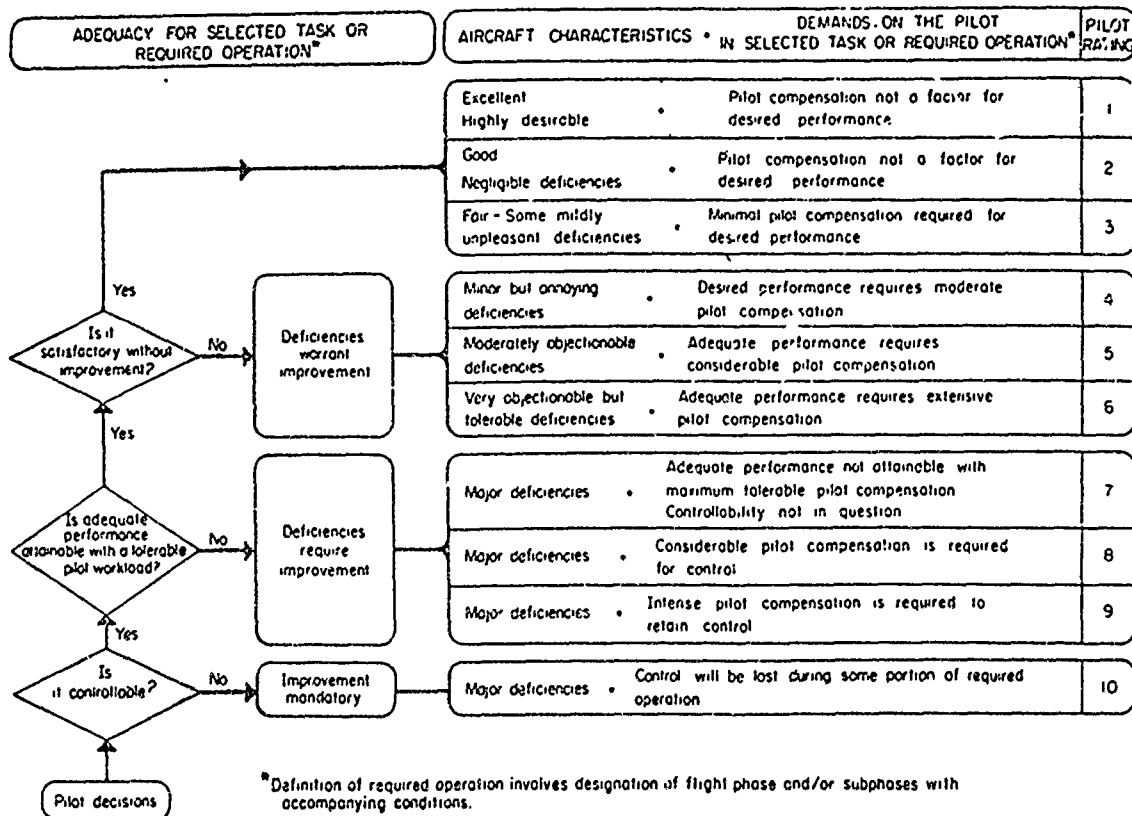
C. Data Analysis

1. Reduction of Experimental Data

a. Flying Qualities Results

Pilot ratings and comments were obtained for each test case. Corresponding pilot-selected control sensitivities were also recorded. For some of the test cases, however, control sensitivities were preset at acceptable levels to save time. The pilot ratings were based on the Cooper-Harper scale (Table IV) and the pilots' comments consisted of responses to the appropriate parts of the questionnaire shown in Table V. The rating scale and questionnaire are very similar to those used in the Norair VIFCS program (Ref. 9). For presentation in the figures the UARL fixed-base rating data and control sensitivity results were each averaged over pilots A and B. The corresponding moving-base data from pilot B are shown separately. Also, Calspan pilot evaluation results were never averaged with the UARL data. Except for height and directional control, the Calspan pilots did not reach the level of control proficiency on the UAC simulator which is necessary to provide valid flying qualities data. This should not be interpreted as a reflection on the capabilities of the Calspan evaluation pilots who were both highly skilled in the control of V/STOL aircraft. Rather, the inability to become proficient, in the somewhat limited time available for Calspan pilot training, was a result of the complex nature of the UAC contact analog display (Fig. 3). This display does not provide a great deal of visual realism and in order to control properly one must rely on the relative motion between the cross and square symbols. The Calspan pilots did not learn to "lead" their control inputs properly using this relative motion information. They also tended to make control inputs of the wrong polarity, because it was difficult for them to determine the proper correlation between the symbol relative motion and the required control input. Valid flying qualities data can be obtained with the UAC display, however, for evaluation pilots who are familiar with its characteristics (e.g., Refs. 7, 8, and 12). For such pilots, the UAC display can provide visual cues (except for peripheral information) which are similar to those in actual VFR flight, and in some aspects possibly better than VFR cues (Ref. 7).

TABLE IV
COOPER-HARPER PILOT RATING SCALE



All the rating and control sensitivity data for the UARL pilots are summarized in Appendix A and the corresponding pilot comments are contained in Appendix B. Similar results from Calspan pilot B are presented in Appendix D.

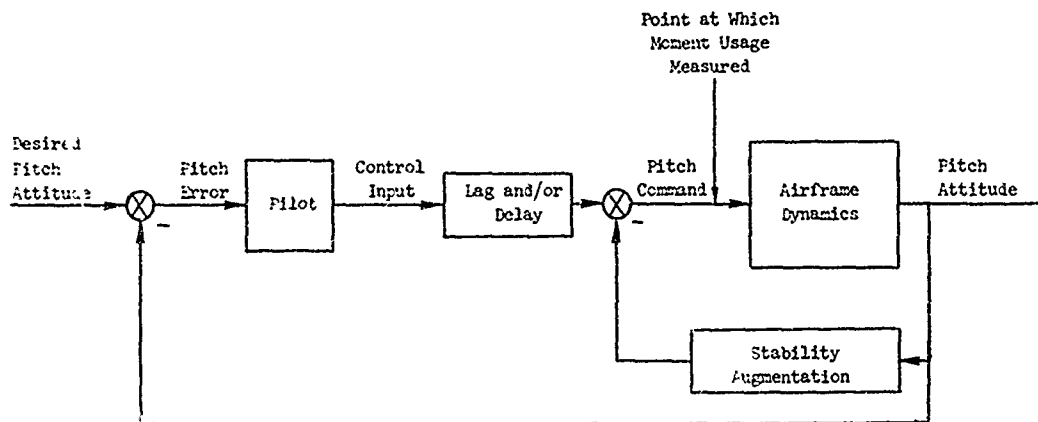
b. Control Power Data

The total pitch, M_C , roll, L_C , and yaw, N_C , control moments (pilot control inputs plus that from the rate damping and attitude stabilization derivatives, i.e., the stability augmentation system commands) were measured for each test case in the longitudinal and lateral control and the directional control investigations. Pitch control moment and thrust-usage data were measured during the height control study. A representative schematic showing the point at which the pitch control-moment-usage data were measured

TABLE V
UARL FLYING QUALITIES QUESTIONNAIRE

- | | |
|--|--|
| I. Comment on selection of control sensitivities. | D. Precision: hover and vertical landing. |
| II. Comment on the following flying qualities areas. | 1. Ability to establish and maintain precision hover. |
| A. Air-taxi-around-the-square. | a. Attitude and angular rates. |
| 1. Response to control inputs (all axes). | b. Position. |
| 2. Ability to initiate motion (each direction). | 2. Adequate for vertical landing? |
| 3. Ability to stabilize and hold desired velocities. | 3. Control activity. |
| 4. Ability to stop precisely and come to hover at corners. | E. Secondary dynamics. |
| 5. Are excessive attitude changes (pitch and roll) required? | 1. Did dynamics for one axis affect your control of another axis? |
| 6. Ability to hold heading, altitude. | III. Overall evaluation. |
| 7. Control deflections, trim. | A. Objectionable features. |
| B. Quick stops. | B. Favorable features. |
| 1. Can you stop as quickly as you would like? | C. Special piloting techniques. |
| 2. Are excessive attitude changes required? | D. Pilot rating; why? |
| 3. Ability to hold heading and altitude. | |
| 4. Control motions required. | |
| C. Turn-over-a-spot. | IMPORTANT: PLEASE AVOID ALL REFERENCE AND COMPARISONS TO ANY OTHER FLIGHT. MAKE EACH SET OF COMMENTS INDEPENDENT OF ANY OTHER. |
| 1. Ability to remain over spot. | |
| 2. Attitude control (pitch and roll), height control. | |
| 3. Ability to initiate and hold turn rate. | |
| 4. Ability to stop on preselected heading. | |
| 5. Comment on use of wing-tilt control. | |

is shown in Sketch II-G. Control moment for roll and yaw control and thrust usage for height control were measured at corresponding points in the appropriate control loop. These control power data were recorded on an FM tape



SKETCH II-G. Representative (Pitch) Aircraft Control Loop Showing Point at Which Control-Moment Usage was Measured

recorder. Control power usage for the experiments in which effectively unlimited control power was available was characterized by the percent time given moment levels were exceeded for a particular subtask. For those investigations in which control power was limited, the percent time that total control power commands exceeded these limits was of interest. The exceedance percentages were computed off-line from the recorded control power data using an analog computer. Exceedance computations were performed on the magnitudes of the pitch, roll and yaw control moment data; $|M_C|$, $|L_C|$, $|N_C|$, respectively, and the combined pitch and roll moment results, $|M_C| + |L_C|$, from the longitudinal and lateral studies and from the directional control investigations. As indicated by the relationship $(|M_C| + |L_C|)$ the exceedance percentages for the combined pitch and roll signal were performed on the sum of the magnitudes of total pitch and roll control moments. For the height control data, the exceedance computations were performed on $|M_C|$ and on the negative or "up" collective part of $Z_{\delta_C} \cdot \delta_C$ and $Z_{\delta_C} \cdot \delta_C + Z_{W_S} \cdot W$. It was felt that exceedance percentages computed from the thrust used to ascend or arrest sink rates would be more significant than percentages based on both positive and negative thrust usage about the trim level ($T/W = 1.0$).

Representative plots of exceedance results are shown in Fig. 5. There the percent time that $|M_C|$, $|L_C|$ and $|M_C| + |L_C|$ exceed the given reference levels are shown with subtask as a parameter. These data are for one pilot and are plotted on a probability grid. For the type of plots in Fig. 5, a

straight line indicates that the data can be characterized by a Gaussian probability distribution. There is some tendency for the curves from the hover and turn subtasks to exhibit this characteristic.

To simplify the task of evaluating the effects of a variety of aircraft and task parameter changes on control power usage, the control power level exceeded 5 percent of the time was chosen for comparison. The 5-percent level was selected because it is generally near the upper limit of control power used by the pilot and would presumably be related to the required installed power. A previous UARL study showed some evidence to support this assumption (Ref. 13). On the other hand, it is not such a small percentile that it would be an unreliable indicator of overall control power usage. The data in Fig. 5, for example, indicate that if the 5-percent level is used to rank the subtasks as to control-moment usage, the results are consistent with the trends evident over all percentiles. However, the 5-percent level should be more sensitive to parameter changes than larger percentile levels.

The 5-percent level results presented in this report were averaged over the two pilots participating in the study and over both moving- and fixed-base data to provide the largest possible data sample for a given test point. Averaging the moving- and fixed-base data appeared to be valid since the differences in these two types of data were less than the inter-pilot variation. That is, there was generally no dramatic difference between fixed- and moving-base data. Representative results which support this conclusion are shown in Fig. 6.

2. Analytical Investigations to Interpret the Data

Two types of analytical efforts were undertaken to interpret and rationalize the experimental results. One involved converting the parameters in MIL-F-83300 which specify satisfactory V/STOL response into functions which could readily be compared with the UARL flying qualities and control power data. The computations were performed to permit evaluation of the MIL-F-83300 requirements for control sensitivities, control power and satisfactory levels of control lags and delays.

The second type of analytical investigation was man-machine analysis of the different control loops (longitudinal, lateral, height and directional) closed by the pilot when controlling a V/STOL aircraft. The results of these analyses were used to select parameters to be considered in the experimental studies and to interpret pilot opinion data in terms of the pilot lead and gain compensation required. The closed-loop models and analytical techniques used here are discussed in detail in previous UARL reports (e.g., Refs. 7, 8 and 14).

SECTION III

RESULTS OF LONGITUDINAL AND LATERAL CONTROL STUDIES

This section consists of two parts in which the results of the longitudinal and lateral control studies are discussed. Part A is concerned with flying qualities data and Part B with control-moment usage data. Details of the experimental design, the equipment and procedures and other background material are given in Section II.

A. Flying Qualities Results

Pilot ratings and pilot-selected control sensitivities from the studies of (1) turbulence, (2) control lags and delays, (3) control moment limits, (4) control moments through stored energy, (5) inter-axis motion coupling, (6) thrust-vector control independent of attitude, and (7) rate-command/attitude-hold control are discussed here. The data are interpreted using man-machine analysis methods and, where appropriate, are compared with MIL-F-83300.

1. Turbulence

a. Pilot Ratings

The flying qualities of the six basic configurations were each evaluated at three turbulence intensities ($\sigma_{u_g} = \sigma_{v_g} = 3.4, 5.8$ and 8.2 ft/sec) to determine the sensitivity of representative Level 1, 2 and 3 V/STOL aircraft to changes in turbulence intensity. Pilot ratings from these evaluations (Cases T1 through T18, Table A-II) are presented in Fig. 7. The pilots were not aware of the turbulence intensity level present for a given test case. As might be expected, the ratings generally deteriorated as gust intensity increased. However, it appears that the rate of deterioration may have been greater for configurations with the less stable (Levels 2 and 3) dynamics. For example, there was no degradation in ratings for the Level 1 configurations as rms turbulence intensity was increased from 3.4 to 5.8 ft/sec. A general increase in rating for the Level 1 configurations is evident, however, at the 8.2 -ft/sec intensity, although the ratings all remain in the acceptable region (Fig. 7(a)). A much more definite deterioration in ratings is evident for the Level 2 and 3 configurations, especially for the change in turbulence intensity from 3.4 to 5.8 ft/sec.

The degradation in rating is shown more clearly in Fig. 8 where it is plotted versus configuration flying qualities level, with the change in turbulence intensity treated as a parameter. The degradation in fixed-base ratings for Level 2 and 3 configurations is much greater than that for Level 1 configurations over the turbulence intensity interval 3.4 to 5.8 ft/sec. Except for

BC4, which is Level 1 but relatively responsive to gusts, this trend is also evident (to a lesser extent) for the intensity interval 3.4 to 8.2 ft/sec. There is not sufficient moving base data to permit a complete comparison between levels. However, over the turbulence interval 3.4 to 8.2 ft/sec, the degradation in moving-base ratings for Level 1 configurations BC1 and BC4 is less than the corresponding fixed-base degradation. The moving-base degradation for BC5 is greater than its fixed-base counterpart but still smaller than the fixed-base degradation for the Level 2 and 3 configurations. In summary, the pilot rating data would tend to indicate (but by no means confirm) that the MIL-F-83300 Level 1 requirement for V/STOL pitch, roll and yaw dynamic response (paragraph 3.2.2) provides aircraft dynamics which remain quite controllable for nominal increases in turbulence intensity.

The rating data can be interpreted by considering the aircraft attitude and position response to turbulence and the phase lags of the attitude dynamics at frequencies critical to pilot control. It has been shown (Refs. 7 and 8) that pilot rating is related to both the workload involved in suppressing turbulence and the lead compensation he must supply to provide good closed-loop attitude characteristics. This lead compensation is inversely dependent on the attitude phase lags over the frequency interval from about 1 to 4 rad/sec (Refs. 7 and 14). The frequency domain characteristics of the open-loop attitude and position response to turbulence for the six basic configurations are shown in Figs. 9 and 10. The phase lags contributed by the pilot and the open-loop attitude dynamics for these configurations are presented in Fig. 11. The pilot's lags are assumed to consist of a pure delay of 0.09 sec in combination with a first-order lag having a 0.2-sec time constant (Refs. 7 and 14). An examination of the phase lag and turbulence response curves will indicate why the Level 1 configurations BC1 and BC5, and to a lesser extent, BC4, have generally better flying qualities and are less affected by turbulence than the Level 2 and 3 configurations. The phase lags (Fig. 11) for BC1, BC4 and BC5 are all appreciably smaller than those for the Level 2 and 3 configurations over the critical frequencies ($\omega = 1.5$ to 4 rad/sec, Fig. 11). This indicates that the pilot need supply less lead compensation to provide good attitude control characteristics. Also, the normalized open-loop attitude and position power spectral densities for BC1 and BC5 are appreciably smaller than those for the Level 2 and 3 configurations. The power spectral densities for BC4, the remaining Level 1 configuration, are comparable to those for BC2, BC3 and BC6 over the lower frequencies but are smaller at the higher frequencies which are more difficult for the pilot to suppress. Consequently, the opinion ratings for BC4 might be expected to exhibit a somewhat smaller sensitivity to gust intensity than BC2, BC3 and BC6.

b. Control Sensitivities

Longitudinal and lateral control sensitivity data are shown in Figs. 12 and 13, respectively. For most of the six configurations, the longitudinal control sensitivities, M_{δ_e} , tend to increase with turbulence intensity. This trend reflects the pilot's requirement for more rapid attitude and position responses to control inputs as he tried to maintain performance in the presence of increasing gust disturbances. For some of the configurations (BC4, BC5 and BC6) the lateral control sensitivities (Fig. 13) tend to increase with turbulence intensity, but this trend is not consistent for all configurations. In fact, the control sensitivities selected for BC3 tend to decrease slightly for the larger gusts. Such inconsistencies are not unexpected, since previous studies have shown that a fairly broad range of control sensitivities are acceptable to most pilots (Refs. 7 and 9). Figures 12 and 13 also contain boundaries for the maximum and minimum control sensitivities permitted under the MIL-F-83300 specification for aircraft attitude response to control inputs (paragraph 3.2.3.2). These sensitivity boundaries were back-calculated using the attitude response specifications and the known aircraft dynamics. It is apparent from the distance between these boundaries that the specification permits appreciable latitude in the installed V/STOL pitch and roll sensitivities. The values of M_{δ_e} and L_{δ_a} selected by the UARL pilots generally fall within these boundaries, but are much closer to the minimum acceptable level than the maximum. In fact, for the Level 1 configurations (BC1, BC4 and BC5), most of the lateral control sensitivities are somewhat below the lower boundary. Larger minimum values are required by MIL-F-83300 for lateral control sensitivities than longitudinal, assuming the pitch and roll dynamics are symmetrical. In studies at UARL, however, L_{δ_a} has generally been found to be smaller than M_{δ_e} (Refs. 7 and 8).

2. Control Lags and Delays

a. Pilot Opinion Ratings

Pilot rating data from the three parts of the control lag and delay investigation are discussed in the following order: (1) first-order control lags, (2) first-order control lags in combination with a 0.1-sec delay, and (3) second-order control lags. The test cases evaluated in these studies were LL1-LL27 and results of the evaluations are summarized in Table A-III (Appendix A).

The effects of the first-order control lags on ratings are shown in Fig. 14. These lags affected only the pilot's control stick commands and not the SAS inputs. Also, the lags were identical for both pitch and roll. As might be expected, the ratings generally deteriorated as the lag time constant, $\tau_e = \tau_a$, increased. However, the sensitivity of a given configuration's flying qualities to the lag time constant appeared to correlate with

the flying qualities level (without lags) of the configuration. For example, most of the ratings for the Level 1 configurations at $\tau_e = \tau_a = 0.6$ sec were within one unit of the ratings given for no lags. The Level 2 and 3 configurations generally show a noticeable deterioration in rating at $\tau_e = \tau_a = 0.3$ sec. The degradation in rating is plotted versus flying qualities level in Fig. 15 with the change in lag time constant as a parameter. There is considerable scatter in these results, but the fixed-base data generally show that the degradation in rating was greater for the Level 2 and 3 configurations.

The Level 1 configurations should be somewhat less sensitive to control lags. The primary effect of the control lags is to introduce phase lags (Fig. 16) which increase the need for pilot lead compensation. They do not affect the aircraft response to turbulence. The Level 1 configurations require little lead compensation without lags because their open-loop phase lag is small (Fig. 11). Pilots will tolerate nominal requirements for lead compensation without a significant change in rating (Refs. 7 and 14). Consequently, the ratings for Level 1 configurations do not change appreciably until the lag time constant reaches a relatively large value (e.g., $\tau_e = \tau_a = 0.6$). However, for the Level 2 and 3 configurations the requirements for pilot compensation are at a relatively high level with no lags (Fig. 11). In this situation the pilots appear to be more sensitive to the increased lead requirements, possibly because it is more difficult to supply the needed increment. Note that the magnitude characteristics of the basic configuration-lag combination, which will not be discussed here, may also affect pilot opinion (Refs. 14 and 15).

The specifications for pitch and roll control system lags can be evaluated using the pilot rating data in Fig. 14. The specification (paragraph 3.2.4) is based on the time it takes aircraft attitude to reach the initial maximum angular acceleration, $t_{\dot{\theta}_{\max}}$ and $t_{\dot{\phi}_{\max}}$, after the initiation of the control command. If these times are less than 0.3 sec the attitude dynamics are considered satisfactory. Values of these times have been computed with $\tau_e = \tau_a = 0.1, 0.3$, and 0.6 sec for each of configurations BC1, BC4 and BC5 and they are summarized in Table VI along with the associated pilot ratings. These results show that the specification permits a $\tau_e = \tau_a = 0.3$ sec for the configurations evaluated; these cases were also generally rated satisfactory. The specification would preclude $\tau_e = \tau_a = 0.6$ sec although the fixed-base ratings remained marginally satisfactory for these cases. However, the moving-base ratings for the first-order control lag evaluation were generally worse than the fixed-base results. Consequently, it would appear that excluding control lags much greater than $\tau_e = \tau_a = 0.3$ sec, as the specification does, is prudent.

TABLE VI

COMPARISON BETWEEN PILOT OPINION RATINGS AND THE
MIL-F-83300 REQUIREMENT FOR ACCEPTABLE ATTITUDE CONTROL LAGS

| Basic Conf. | Lag Time Constant, $\tau_e = \tau_a$, sec | Time to Max. Acceleration, $t_{\ddot{\theta}_{\max}} =$ $t_{\ddot{\phi}_{\max}}$, sec | Average Pilot Rating | |
|----------------|---|--|----------------------|---------------------|
| | | | Fixed Base Mode | Moving-Base Mode |
| BC1 | 0.1 | 0.19 | 2 | 5.5 |
| | 0.3 | 0.31 | 2.75 | |
| | 0.6 | 0.38 | 2.5 | |
| BC4 | 0.1 | 0.15 | 2 | 3.5 |
| | 0.3 | 0.29 | 2.75 | 5 |
| | 0.6 | 0.46 | 3.5 | |
| BC5 | 0.1 | 0.18 | 2 | 3 |
| | 0.3 | 0.30 | 2 | |
| | 0.6 | 0.38 | 3.5 | |

The effects of adding a 0.1-sec time delay in pitch and roll response for Level 1 and 2 configurations (level designation applies for no lags or delays) are shown in Table VII. Such delays also increase the requirements for pilot adapted lead compensation by increasing the phase lags in the attitude response to control inputs. However, as indicated in Fig. 16, a 0.1-sec delay contributes relatively small phase lags over the frequency range (~ 1 to 4 rad/sec) most critical to pilot control of attitude. Time delays greater than 0.1 sec were not considered since the specification (paragraph 3.2.4) excludes them. In this study the time delays ($d_e = d_a$) were added separately and in combination with first-order lags ($\tau_e = \tau_a$) having 0.3-sec time constants. For one of the cases (indicated by the superscript 2 in Table VII) the time delays and lags affected both the pilot's control inputs and the SAS commands. For all other cases the time delays and lags operated only on the control input. For the Level 1 configuration (BC1) the 0.1-sec time delays in the pilot's pitch and roll control inputs had little effect on pilot rating, whether or not the 0.3-sec lags were also present. For example, adding $d_e = d_a = 0.1$ sec with $\tau_e = \tau_a = 0$ did not change the pilot's rating (PR = 2 for both cases). Also, adding $d_e = d_a = 0.1$ with $\tau_e = \tau_a = 0.3$

TABLE VII

EFFECTS OF TIME DELAYS AND CONTROL SYSTEM LAGS ON PILOT RATINGS

BC1 is Level 1 and BC2 is Level 2 Without Lags and Delays

| Basic Conf. | Lag Time Constant, $\tau_e = \tau_a$, sec | Time Delay $d_e = d_a$, sec | Ratings from Pilot B for Fixed-Base Mode |
|------------------|--|------------------------------------|---|
| BC1 ¹ | 0 | 0 | 2 |
| | 0 | 0.1 | 2 |
| | 0.3 | 0 | 2.5 |
| | 0.3 | 0.1 | 3 |
| | 0.3 ² | 0.1 ² | 8 ² |
| BC2 ¹ | 0 | 0 | 5 |
| | 0 | 0.1 | 5 |
| | 0.3 | 0 | 5 |
| | 0.3 | 0.1 | 7 |

1. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative; pitch and roll lags and delays equal.
2. For this case the lag and delay operated on both the control input and the SAS command. For all the other cases only the control input was affected.

resulted in a pilot rating deterioration of only 0.5 units relative to the rating with only the 0.3-sec lags. However, the results in Table VII show a dramatic change in rating when the lags and delays were relocated so that they affected both the control and SAS commands (PR = 8 versus PR = 3). In this case, the stability augmentation was much less effective and, as a result, the configuration was very difficult to control. The pilot's chief complaint (Case LL25, Table B-II, Appendix B) was that large pitch oscillations developed; it was nearly impossible to damp them and stabilize pitch attitude. The results for the Level 2 configuration (BC2) also show little change when $d_e = d_a = 0.1$ were added with $\tau_e = \tau_a = 0$ sec. However, when the same delays were added to BC2 with $\tau_e = \tau_a = 0.3$ the associated pilot rating was two units worse than for the lags without the delays (PR = 7 versus PR = 5). Note, however, that the rating for the lags alone was somewhat better than would be expected. That is, it is the same rating (PR = 5) as was assigned to BC2 with neither lags nor delays present in the control response. The

results in Table VII, although limited, would tend to indicate that 0.1-sec delays in the pilot's pitch and roll control responses are acceptable, at least for Level 1 configurations. That is, the specification (paragraph 3.2.4) which permits delays in the pitch or roll attitude response to control inputs of up to 0.1 sec, appears to be reasonable.

Second-order lags were also evaluated during this study to provide some information on the generality of the MIL-F-83300 specification for control lags. The specification is based on the results of studies with first-order control lags; however, because it is phrased in terms of an angular acceleration response which must be achieved within a reference time interval, it may also apply to more general lags. Four sets of parameters for the second-order lag were evaluated ($\omega_{n_e} = \omega_{n_a} = 3.33$ rad/sec with $\zeta_e = \zeta_a = 0.22, 0.50$, and 1.0 and $\omega_{n_e} = \omega_{n_a} = 8.23$ with $\zeta_e = \zeta_a = 1.0$). As for the first-order lag study the lags only affected the pilot's control response and they were identical in pitch and roll. The initial combination of parameters was selected to have the same break frequency ($\omega_n = 3.33$) as that for an acceptable first-order lag ($1/\tau_e = \omega_{n_e}$ where $\tau_e = 0.3$). The damping ratio, $\zeta_e = \zeta_a$, was adjusted to give the same phase lag as that from the first-order lag in the region of the pilot's crossover frequency ($\omega_c = 2.5$ to 3 rad/sec; see Refs. 8 and 14). Consequently, the lead compensation requirements for the two lags would be similar. However, the nature of the control stick response would be quite different because of the lightly damped ($\zeta_e = \zeta_a = 0.22$) oscillations present for the second-order lag. The magnitude and phase characteristics of the open-loop pilot and attitude dynamics, without pilot lead or gain compensation, are shown in Fig. 17.

Results from the evaluation of second-order lags with configuration BCl (Fig. 18) show that the combination of parameters ($\zeta = 0.22, \omega_n = 3.33$) selected for equivalence with $\tau_e = \tau_a = 0.3$ resulted in a pilot rating of 10. Pilot comments indicated that the oscillatory pitch and roll motion was completely unacceptable. The ratings improved with increased damping ratio, but a satisfactory rating was not obtained even with $\zeta_e = \zeta_a = 1.0$. Here the oscillatory dynamics were not a problem, but lead compensation was needed to compensate the phase lags. Pilot rating was satisfactory for this damping ratio, however, with the larger natural frequency, $\omega_{n_e} = \omega_{n_a} = 8.23$ rad/sec. The attitude phase lags in the region of pilot crossover frequency (2.5 to 3.5 rad/sec) were somewhat smaller with these parameters. The pilot rating results from Fig. 18 are compared with $t_{\theta_{\max}} = t_{\phi_{\max}}$ values computed for the second-order lag test cases in the following tabulation:

| $\omega_{n_e} = \omega_{n_a}$, rad/sec | $\zeta_e = \zeta_a$ | $t_{\theta_{\max}} = t_{\phi_{\max}}$ | PR |
|---|---------------------|---------------------------------------|----|
| 3.33 | 0.22 | 0.61 | 10 |
| 3.33 | 0.50 | 0.58 | 7 |
| 3.33 | 1.0 | 0.55 | 4 |
| 8.23 | 1.0 | 0.33 | 3 |

The only case rated satisfactory also had a time to maximum angular acceleration which was nearly equal (0.33 sec) to that required by the specification (0.30 sec). However, $t\ddot{\theta}_{\max} = t\ddot{\phi}_{\max}$ was almost twice the specification value (0.55 sec) at $\omega_{n_e} = \omega_{n_a} = 3.33$ rad/sec and $\zeta_e = \zeta_a = 1.0$ for a test case rated marginally satisfactory (PR = 4). These very limited results indicate, then, that the control lag specification may not be sufficiently general to apply to second-order control lags.

b. Control Sensitivities

Longitudinal and lateral control sensitivities from the investigation of first-order control lags are presented in Figs. 19 and 20, respectively. It might be expected that pilot-selected control sensitivities would increase somewhat with lag time constants since the lags result in slower attitude response. For the longitudinal sensitivities, M_{δ_e} , there is little evidence of this except possibly for configuration BC3 (Fig. 19). The lateral sensitivities, L_{δ_a} , exhibit some tendency to increase with τ_a and, again, this effect is more pronounced for BC3. Configuration BC3 is Level 3 and very difficult to control as the lags become larger. The pilots may have increased sensitivity in an attempt to more quickly attenuate the large attitude excursions which tended to develop for $\tau_e = \tau_a = 0.3$ and 0.6 sec.

Boundary values for acceptable minimum and maximum longitudinal and lateral control sensitivities developed from the MIL-F-83300 specification for attitude control response (paragraph 3.2.3.2) are shown for the Level 1 configurations in Table VIII. Both the minimum and maximum boundaries increase with $\tau_e = \tau_a$ because the specification is written in terms of an acceptable response after a given time period. Because the lags slow the attitude control response, the sensitivities must increase to satisfy the specification. For the small lag time constants the pilot-selected lateral and longitudinal sensitivities are close to the specification's lower boundaries (M_{δ_e} and L_{δ_a} are averages of fixed- and moving-base data). For the larger time constants the sensitivities fall below the minimum boundaries. Note also that the maximum sensitivity boundaries are very much larger than the UARL selected values. It may be appropriate to lower the minimum boundaries somewhat and it would seem that the maximum boundaries also could be reduced. The maximum allowable sensitivities would, in general, result in extremely "touchy" aircraft pitch and roll response to control inputs and could cause the pilot to overcontrol.

TABLE VIII

COMPARISON OF AVERAGED LONGITUDINAL AND LATERAL CONTROL SENSITIVITIES
FROM THE CONTROL LAG STUDY WITH THE MIL-F-83300 REQUIREMENTS

| Basic Conf. | Lag Time Constant, $\tau_e = \tau_a$, sec | UARL M_{δ_e} | MIL-F-83300 M_{δ_e} Boundaries | | UARL L_{δ_a} | MIL-F-83300 L_{δ_a} Boundaries | |
|----------------|---|------------------------|--|-------|------------------------|--|-------|
| | | | Min. | Max. | | Min. | Max. |
| BC1 | 0 | 0.291 | 0.233 | 1.560 | 0.271 | 0.312 | 1.560 |
| | 0.1 | 0.303 | 0.261 | 1.740 | 0.244 | 0.348 | 1.174 |
| | 0.3 | 0.311 | 0.342 | 2.278 | 0.223 | 0.456 | 2.278 |
| | 0.6 | 0.372 | 0.490 | 3.268 | 0.312 | 0.654 | 3.268 |
| BC4 | 0 | 0.342 | 0.258 | 1.721 | 0.302 | 0.344 | 1.721 |
| | 0.1 | 0.404 | 0.291 | 1.940 | 0.334 | 0.388 | 1.940 |
| | 0.3 | 0.403 | 0.384 | 2.561 | 0.321 | 0.512 | 2.561 |
| | 0.6 | 0.412 | 0.552 | 3.683 | 0.384 | 0.737 | 3.683 |
| BC5 | 0 | 0.293 | 0.233 | 1.560 | 0.243 | 0.312 | 1.740 |
| | 0.1 | 0.304 | 0.261 | 1.738 | 0.241 | 0.348 | 1.738 |
| | 0.3 | 0.283 | 0.343 | 2.288 | 0.220 | 0.458 | 2.288 |
| | 0.6 | 0.324 | 0.489 | 3.263 | 0.301 | 0.635 | 3.263 |

3. Control Moment Limits

In this study the installed control moments required for pilot acceptance were determined for several of the basic configurations (BC1, BC4, BC5 and BC6). The correlation between the requirements for control moment and the levels exceeded some given small percent of the time with unlimited moment available, i.e., the 5-percent level, was also examined. This study was performed with and without control system lags and delays. Also, the pilots were not aware of the control-moment limits except as they affected flying qualities. Results from this study are listed for Cases LM1-LM25 in Table A-IV in Appendix A.

The effects of control-moment limits on pilot rating of the flying qualities of configurations BC1, BC4, BC5 and BC6 are presented in Fig. 21. The reference limits or starting points for the installed control-moment levels (pitch, roll, and yaw) were averages of those levels exceeded 5 percent of the time (\overline{CM}_5) with unlimited moment available (see Section III.B.1.d). These averages were computed over all subtasks, pilots and modes of simulator operation (fixed- and moving-base). The control-moment limits for the remaining test cases were obtained by increasing (or decreasing) the reference

levels by integral multiples of 10 percent. Also, the limits were applied to the total control moment available for both control inputs and the SAS commands. Note that \bar{CM}_5 is different for each configuration and its magnitude scales approximately with the configuration's speed-stability parameters (see Table C-I, Appendix C).

Only for configuration BC5 did control-moment limits equal to the average 5-percent exceedance level, \bar{CM}_5 , result in ratings equivalent to those of unlimited moments (Fig. 21). Configuration BC5 is a very stable, Level 1 configuration with little response to turbulence. For configuration BC1, which is identical to BC5 except that its drag parameters are one-fourth as large, control moment limits at least 1.2 times the reference \bar{CM}_5 level were needed to obtain ratings equivalent to those for unlimited moments. For the configurations which were more responsive to turbulence (BC4) or both less stable and more responsive to turbulence (BC6), control-moment limits of 1.3 times the \bar{CM}_5 levels were required for equivalent ratings. For all the configurations examined, a deficiency in control moment was most evident as a momentary inability to control pitch, and to a lesser extent roll, when performing the maneuver and quick-stop subtasks. Pilot comments indicated that the limits on yaw control moment did not affect flying qualities.

Table IX contains a comparison between the control-moment limits found to be necessary for pilot acceptance in this study and the control-moment

TABLE IX
COMPARISON OF UARL ACCEPTABLE CONTROL-MOMENT
LIMITS WITH MIL-F-83300 REQUIREMENTS

| Conf. | Control Moment Source | Installed Control Moment, rad/sec ² | | |
|-------|-----------------------------|--|-------------------|------------------|
| | | Pitch, M_{cm} | Roll, L_{cm} | Yaw, N_{cm} |
| BC1 | UARL MIL-F-83300 | 0.40 | 0.46 | 0.13 |
| | | 0.57 | 0.47 | 0.31 |
| BC4 | UARL MIL-F-83300 | 1.07 | 0.79 | 0.23 |
| | | 1.26 | 0.81 | 0.31 |
| BC5 | UARL MIL-F-83300 | 0.38 | 0.36 | 0.15 |
| | | 0.57 | 0.48 | 0.31 |
| BC6 | UARL MIL-F-83300 | 1.16 | 0.98 | 0.22 |
| | | 1.18 | 0.71 | 0.31 |

requirements in MIL-F-83300. The control moment specification (paragraph 3.2.3.1) stipulates that sufficient control moment must remain at the maneuvering airspeed to simultaneously produce aircraft pitch, roll, and yaw attitude changes of ± 3 deg, ± 4 deg, and ± 6 deg, respectively, within one second. The specification values shown in Table IX were computed assuming longitudinal and lateral maneuvering speeds equivalent to those used in the UARL task (≈ 15 ft/sec). Combining these airspeeds with the mean wind increases the effective longitudinal airspeed to ≈ 32 ft/sec. For the UARL simulation, then, the aircraft must have sufficient pitching moment, M_{cm} , to trim the 32-ft/sec airspeed and also to provide the ± 3 deg pitch change within one second. The roll, L_{cm} , and yaw, N_{cm} , moments need only be sufficient to trim the 15-ft/sec lateral airspeed and provide the required attitude changes (± 4 deg and ± 6 deg, respectively).

The results in Table IX show that for all the Level 1 configurations (BC1, BC4, BC5) the pitch and roll control-moment requirements from MIL-F-83300 equalled or exceeded those found to be necessary in the UARL study. For BC6, a Level 2 configuration which is quite responsive to gusts, the specification value for L_{cm} was about 20 percent low. However, the UARL level for M_{cm} agrees well with the corresponding MIL-F-83300 value. Also, all of the specification levels for N_{cm} were well in excess of the UARL results. It would appear from these relatively limited data that the MIL-F-83300 requirement for pitch and roll control moments is adequate. However, the yaw control-moment requirement seems somewhat excessive. Pilots never noticed a deficiency in yaw control moments during the UARL study even for levels of N_{cm} considerably lower than the UARL data shown in Table IX. Limitations on pitch and roll control moment were predominant in the formation of rating. The MIL-F-83300 yaw control-moment requirement is discussed in more detail in Section V.A.3.

It was pointed out previously that another objective of this study was to determine whether the required levels for installed control moments correlated with the percent time given pitch and roll moment levels were exceeded with unlimited moments available. In particular it was thought that the 5-percent exceedance level might be sufficient. The results in Fig. 21 do not appear to substantiate such an hypothesis. However, it may be that the maximum of the 5-percent exceedance levels measured for the different subtasks should have been used for \overline{CM}_5 instead of the average over all subtasks. These maximum values, averaged over both pilots and fixed- and moving-base simulator modes (Table C-I, Appendix C), are listed in Table X along with the pitch and roll moment levels necessary for pilot ratings approximately equivalent to those for unlimited control moment (Fig. 21).

TABLE X

COMPARISON OF MAXIMUM FIVE-PERCENT EXCEEDANCE MOMENT
LEVELS USED FOR ANY SUBTASK WITH ACCEPTABLE LIMITS
ON INSTALLED ROLL AND PITCH CONTROL MOMENTS

| Basic Conf. | Control Moment | Maximum 5-Percent Level | Acceptable Moment Level |
|----------------|-------------------|----------------------------|----------------------------|
| BC1 | M_c | 0.34 | 0.43 |
| | L_c | 0.45 | 0.50 |
| BC5 | M_c | 0.45 | 0.38 |
| | L_c | 0.50 | 0.36 |
| BC4 | M_c | 0.90 | 1.07 |
| | L_c | 0.62 | 0.78 |
| BC6 | M_c | 0.93 | 1.16 |
| | L_c | 0.94 | 0.98 |

The results in Table X show that only for configuration BC5 were the maximum 5-percent exceedance moment levels equal to or greater than those levels which were acceptable to the pilot. It appears, then, that the 5-percent exceedance level, whether it is composed of the average over all subtasks or the maximum for any subtask, does not provide acceptable levels of installed control moment. If configuration BC5 is considered an anomaly, the fact that control-moment levels of 1.2 to 1.3 times \overline{CM}_5 were acceptable may imply that a lower-percentile exceedance level, e.g., the 1 to 2 percent level, would provide acceptable installed control moments. Results related to this possibility are discussed in Section III.B.2.

The control-moment requirements with control system first-order lags ($\tau_e = \tau_a = 0.3$ and 0.6) and delays ($d_e = d_a = 0.1$ for all test cases) were also evaluated in this study for configurations BC1 and BC5. The procedures used and moment levels considered were identical to those for the evaluation of control-moment limits without lags. The effects of the control lags can be seen in Fig. 22. The necessary control-moment levels were increased by

the control lags and delay. For example, control-moment levels for BCl equal to $1.4 \overline{CM}_5$ were required with $\tau_e = \tau_a = 0.3$ and 0.6 and $d_e = d_a = 0.1$ for ratings equivalent to those with unlimited control moments. Control moments equal to only $1.2 \overline{CM}_5$ were sufficient for BCl without lags and delay (Fig. 21). For configuration BC5, $1.2 \overline{CM}_5$ was required with $\tau_e = \tau_a = 0.6$ and $d_e = d_a = 0.1$. Without the lags and delays the corresponding required moment levels were equal to $1.0 \overline{CM}_5$. The control-moment specification (paragraph 3.2.3.1) will account for the additional control moments required with control system lags and delays. It is stated in terms of minimum attitude responses within a certain time and, consequently, requires more installed control moments when control lags or delays are present. It should be noted, however, that the control moments required by MIL-F-83300 for no lags are generally equal to or greater than the UARL levels necessary with lags and delays. This is illustrated in the following list.

| Basic Conf. | MIL-F-83300 Without Lags | | | UARL Acceptable With Lags | | |
|----------------|-----------------------------|----------------------|----------------------|------------------------------|----------------------|----------------------|
| | $\underline{M_{cm}}$ | $\underline{L_{cm}}$ | $\underline{N_{cm}}$ | $\underline{M_{cm}}$ | $\underline{L_{cm}}$ | $\underline{N_{cm}}$ |
| BC1 | 0.57 | 0.47 | 0.31 | 0.47 | 0.54 | 0.16 |
| BC5 | 0.57 | 0.48 | 0.31 | 0.46 | 0.44 | 0.18 |

Only L_{cm} for configuration BCl from the UARL study is slightly greater than its MIL-F-83300 counterpart. If the control moment specification for L_{cm} is computed with $\tau_a = 0.3$ under the airspeed conditions discussed previously, the MIL-F-83300 requirement for L_{cm} becomes 0.62 rad/sec^2 , an increase of about 35 percent. If the 0.1 sec delay was also considered the percentage increase would be even greater. For $\tau_a = 0.6$ the corresponding level for L_{cm} is 0.81 . In fact, the specification control moment requirement for control systems with acceptable lags may be excessive. For example, a control lag of 0.3 sec is permissible under MIL-F-83300 for both configurations BCl and BC5. However, such a lag will increase the specification control moment requirements by approximately 35 percent to levels which are much greater than those the UARL results would indicate are necessary.

4. Incremental Control Moment Through Stored Energy

For this study the pilot could command a pitch control moment (stored energy effects were not simulated for roll) greater than the installed or continuously available total moment. It was assumed that this additional moment was provided by converting angular momentum from a rotor-propulsion

system into an increment which decayed with time (as the angular momentum was dissipated). A more detailed discussion of this effect and a description of the simulation procedures used are given in Section II.B.1.e. Representative values for the present increment and the rpm decay (and recovery) time, determined from an analysis of XC-142 propulsion system data are $\Delta M_c = 0.3 M_{cm}$ and $\tau_\Delta = 0.05$ to 0.10 sec. Values for τ_Δ of 0.2 may be possible for helicopters. Cases LS1-LS3 were evaluated for the stored energy investigation and flying qualities results are summarized in Table A-V in Appendix A.

The results in Fig. 23 were obtained using values for M_{cm} which resulted in flying qualities that were significantly worse than those for unlimited control moments. The effects of stored energy were then evaluated for different combinations of ΔM_c and τ_Δ . Data are presented for basic configurations BC1, BC4, BC5 and BC6 (M_{cm} was different for each). Some general improvement in opinion is evident in Fig. 23 for $\Delta M_c = 0.30 M_{cm}$ and $\tau_\Delta = 0.10$. Definite improvement is evident for all configurations with $\tau_\Delta = 0.20$, although the ratings are poorer than for unlimited pitch control moment. Note that for $\Delta M_c = 0.50 M_{cm}$ and $\tau_\Delta = 0.20$ the flying qualities of BC1 are rated equal to those for unlimited pitch control moment.

Time histories of M_c , the total pitch control moment, which show the effects of stored energy are presented in Fig. 24. These results were measured for the maneuvering subtask with configuration BC1 and $M_{cm} = 0.36$. The stored energy parameters considered are $\Delta M_c = 0.3 M_{cm}$ (0.11 rad/sec^2) with $\tau_\Delta = 0.1$ and 0.2 sec and $\Delta M_c = 0.5 M_{cm}$ (0.18 rad/sec^2) with $\tau_\Delta = 0.2$ sec. These are the parameters used with BC1 to provide the pilot ratings shown in Fig. 23. The stored energy contribution is evident in Fig. 24 as a peak which decays relatively quickly to the M_{cm} level. Note that there is a reduction in the amount of time that the control moment is limited as the contribution from stored energy is increased.

5. Inter-Axis Motion Coupling

a. Pilot Ratings

Attitude rate coupling (M_p, L_q) and control coupling ($M_{\delta a}, L_{\delta e}$) were evaluated to determine acceptable limits for such effects (Cases LC1-LC8, Table A-VI, Appendix A). A related objective was to determine whether changes to MIL-F-83300 are needed to account for motion coupling. Background information on this study is contained in Section II.B.1.f. Results from the evaluation of motion coupling are shown in Fig. 25. Pilot ratings and control sensitivities are plotted there versus the level of rate coupling with control coupling shown as a parameter. Configurations BC1 and BC2 were evaluated. For most of the results the coupling effects were additive. For example, a positive pitch control input yields a positive pitch rate and since both L_q and $L_{\delta e}$ were negative, the induced rolling moment was also

negative. For one test case coefficients having signs which resulted in cancelling moments ($L_q < 0$, $L_{\delta_e} > 0$ and $M_p > 0$, $M_{\delta_a} < 0$) were also evaluated. Note that the pitch and roll rate coupling levels were always equal as were the values for longitudinal and lateral control coupling.

Pilot rating showed a significant, consistent deterioration with rate coupling (Fig. 25(a)). There were no threshold effects evident in pilot rating as control coupling was changed from zero to $M_p = -L_q = 2$. That is, this level of coupling brought about a deterioration in rating of 2 units and the trend continued as rate coupling was increased. Without rate coupling, control coupling ratios up to $M_{\delta_a}/L_{\delta_a} = -L_{\delta_e}/M_{\delta_e} = 0.5$ brought about only a 1 unit decrement in rating (a value of 0.5 indicates a large amount of control coupling). As rate coupling was added the increase in rating (deterioration) caused by control coupling also became somewhat larger. It appears from Fig. 25(a) that a control coupling ratio of 0.25 could be expected to produce a 0.5 to 1 unit deterioration in rating while a ratio of 0.5 results in a 1 to 1.5 unit increase. The deterioration in rating for configuration BC2 caused by $M_p = -L_q = 2$ and $M_{\delta_a}/L_{\delta_a} = -L_{\delta_e}/M_{\delta_e} = 0.25$ was equivalent to that for BC1 with the same coupling parameters. Also, no change in rating occurred for BC2 when the signs of M_{δ_a} and L_{δ_e} were changed such that the rate and control coupling compensated somewhat for each other.

Attitude rate coupling appeared to have a greater effect on rating than control coupling for the levels considered in this study. The results in Fig. 25(a) would tend to indicate that MIL-F-83300 should restrict rate coupling to magnitudes less than about 1 per sec. Also, control coupling ratios greater than about 0.25 should not be permitted.

b. Control Sensitivities

Both the longitudinal and lateral control sensitivities generally tended to increase with rate coupling (Figs. 25(b) and 25(c)). The pilots apparently felt they needed a more rapid attitude response to control the coupling motion. Also, the control sensitivities for the 0.5 control coupling ratio were slightly larger than those for no control coupling. However, as indicated by the MIL-F-83300 reference lines (Fig. 25(b)), the longitudinal control sensitivities for BC1 are within the specification (the maximum boundary is well above the limits of the plot's ordinate scale). Also, the minimum boundary for BC2 is even lower than that for BC1 (not shown). The lateral BC1 sensitivities (Fig. 25(c)) for low rate coupling are somewhat lower than the minimum boundaries. However, the pilots would have had no difficulty controlling with sensitivities corresponding to the specification minimums. The effect of rate and control coupling on control sensitivities is not specifically accounted for by the MIL-F-83300 paragraph on response to control inputs (paragraph 3.2.3.2). However, the range of sensitivities permitted by MIL-F-83300 is sufficiently large that the increase in M_{δ_e} and L_{δ_a} caused by control coupling does not result in their exceeding the upper boundary.

6. Independent Thrust-Vector Control

Pilot ratings from the evaluation of longitudinal thrust-vector control independent of aircraft pitch attitude (ITVC) are shown in Fig. 26 and summarized under Cases L11-L15 in Table A-VII in Appendix A. Lateral ITVC was not considered. The pilots were instructed to rate aircraft flying qualities based on their ability to perform longitudinal-position control tasks using thrust-vector-angle rotation with a minimum of pitch-attitude changes. Note that for the other parts of the UARL program the pilots could change the thrust vector to offset the effects of the mean wind acting through the longitudinal drag parameter. However, he was not permitted to use it for general position control. For the ITVC evaluation he was required to attempt to control longitudinal position exclusively with thrust-vector-angle rotation.

Two Level 1 configurations (BC1, BC4) and a Level 2 configuration (BC2) were evaluated with ITVC.

For configuration BC1, with thumb-switch thrust-vector control and control-stick pitch control and the thrust-vector angle displayed on the contact analog (Fig. 26(a)), the best ratings obtained were nearly as good as those for conventional thrust-vector control through attitude changes (PR = 2 to 2.5 for BC1 with conventional control). The pilots did not find it difficult to control aircraft position with the thrust-vector angle while regulating attitude. The lack of extensive experience with ITVC may have been the major reason for the slightly poorer ratings compared with those for conventional control.

Pilot B also evaluated ITVC (thumb-switch thrust-vector control) for configuration BC1 with only an instrument-panel display of thrust-vector angle. For this case his rating was somewhat poorer because alternating his attention between the contact analog and the thrust-vector-angle panel display increased the difficulty of the control task. With the thrust-vector angle on the contact analog (the cross symbol moved vertically on the right side of the screen to indicate angle) the pilot could derive both longitudinal position and thrust-vector-angle information simultaneously. It should be noted that a thrust-vector-angle display was essential to the performance of the longitudinal maneuvering task. Without such a display longitudinal position could not be stabilized. The pilots apparently controlled thrust-vector angle as an inner loop and aircraft position as an outer loop. This is similar to closure of the pitch-attitude loop as an inner loop for conventional V/STOL aircraft control systems (Ref. 8).

For configuration BC4 the best pilot ratings for ITVC with thumb-switch thrust-vector control ($PR \sim 4$ for $\dot{\gamma} = 20$ deg/sec, Fig. 26(a)) were slightly poorer than those for conventional control ($PR = 3$ to 3.5). Configuration BC4 (a high-drag configuration) is Level 1 but more responsive to gusts. The larger position disturbances associated with BC4 appear to be the reason that the best overall ratings for this configuration were assigned with $\dot{\gamma} = 20$ deg/sec. Rapid thrust-vector angle rates were needed to control position. For BC2, the Level 2 configuration (with conventional control), the best rating for thumb-switch ITVC ($PR = 4$) was slightly better than that for conventional attitude control ($PR = 4.5$ to 5). Configuration BC2 is Level 2 because of its lightly damped attitude dynamics. It may be that control of this configuration was improved with ITVC, because it was not necessary to change attitude to move the aircraft longitudinally. As a result, attitude motion was not excited to the extent that it was for the conventional control system and the pilot's workload may have been reduced.

Results from the evaluation of stick thrust-vector-angle control and thumb-switch attitude control are shown in Fig. 26(b). The thrust-vector-angle change per inch of stick input (or sensitivity) was varied in this study, but the rate-of-change of pitching moment from the thumb switch was fixed at a predetermined satisfactory value. A 0.1-sec lag in thrust-vector-angle response was also simulated. For configuration BC1 this method of ITVC was satisfactory (Fig. 26(b)), i.e., ratings were similar to those for thumb-switch thrust-vector control. Recall that BC1 has very stable attitude dynamics and little attitude or position response to turbulence. However, configuration BC4 could not be controlled with the stick ITVC and thumb-switch attitude control system. This was due to the difficulty in controlling attitude with the thumb switch for this gust sensitive configuration. The pilot could not pay the necessary attention to attitude control and still control position with ITVC. The result was eventual loss of control. The same comments apply to this type of control for configuration BC2.

The UARL evaluation of thrust-vector control independent of aircraft attitude indicates that it could be an acceptable substitute for conventional attitude control, when properly implemented. For large aircraft with Level 1 dynamics the use of ITVC should provide satisfactory flying qualities while enabling the pilot to avoid pitch (or roll) attitudes that could lead to ground strikes. For aircraft having large drag parameters (X_u, Y_v) ITVC would also enable the pilots to control position without the large attitude angles that result for such aircraft with conventional position control through attitude. However, the results from this study for an aircraft with large drag parameter (BC4, $X_u = Y_v = -0.2$) indicate that position control for such aircraft remains moderately difficult even with ITVC.

7. Rate-Command/Attitude-Hold Control

The attributes of rate-command/attitude-hold control are that it (1) provides a pitch (roll) rate response proportional to pilot stick commands, and (2) maintains aircraft trim attitudes while enabling the pilot to center his control stick (see Section II.B.1.h. for background). Rate-command/attitude-hold control can be developed with a conventional rate and attitude stabilized V/STOL, by inserting an integration between the pilot's control inputs and the aircraft attitude response. However, to provide satisfactory flying qualities the rate damping and attitude stabilization must be increased to offset the phase lag introduced by the integrator. This can be accomplished by increasing the damping ratio, ζ , of the aircraft's oscillatory roots (with rate damping) and increasing the natural frequency, ω_n , of these roots (with attitude stabilization) beyond the attitude-loop crossover frequency ($\omega_c \approx 2.5$ to 3.5 rad/sec, Ref. 8). Representative effects of changes in ζ and ω_n on the magnitude and phase characteristics of the open-loop pilot-pitch attitude (with no pilot compensation) transfer function are shown in Fig. 27. These results show that increasing ω_n reduces the phase lags near the crossover frequencies $\omega_c \approx 2.5$ to 3.5 rad/sec (and, correspondingly, the pilot lead compensation) more than increasing ζ . Cases LRL-LRL5 were evaluated in this study. Flying qualities results for the case are listed in Table A-VIII in Appendix A.

a. Pilot Ratings

The pilot ratings in Fig. 28 for a configuration having the basic air-frame dynamics (i.e., speed stabilities and drag parameters) of BC1 show the effects of both ζ and ω_n for rate-command/attitude-hold control. Ratings are shown in Fig. 28(a) for $\omega_n = 2.80, 3.44, 6.30$ and 7.40 rad/sec. Again, the pitch and roll dynamic characteristics were identical. Several values of ζ were considered for $\omega_n = 2.8$ and 6.3 . The data in Fig. 28(a) indicate that for ω_n in the region of the pitch- and roll-loop crossover frequencies, e.g., $\omega_n = 2.80$ and 3.44 , satisfactory ratings cannot be achieved even with ζ values approaching 1.0. However, for $\omega_n \geq 6.3$ satisfactory ratings resulted for ζ values of 0.5 and possibly lower. Configuration BC4 was evaluated with two natural frequency values ($\omega_n = 4$ and 5 rad/sec) different from those for BC1 to provide a relatively complete map of the effects of natural frequency. There is a significant difference between the moving- and fixed-base data for BC4, but, again, ratings are better for the larger ω_n . It appears, also, that damping ratios in the neighborhood of 0.7 are probably necessary to insure satisfactory flying qualities for these ω_n values. A rate-command/attitude-hold control system was also evaluated for hover and low-speed flight in a previous Boeing study (Ref. 16). In that study an ω_n of 5 rad/sec with $\zeta = 0.9$ resulted in good ratings for lateral flying qualities (PR = 2 to 3 for the optimum control sensitivity) and unsatisfactory ratings were obtained for $\omega_n = 2.5$ rad/sec with $\zeta = 0.9$. These results agree fairly well with the UARL data.

Although the UARL pilots rated a number of the rate-command/attitude-hold test cases satisfactory (LR4, LR6, LR8 and LR15, Table A-VIII, in Appendix A) their comments indicate that it provided no particular benefits for hover and low-speed flight operation. For this type of flight the pilots did not hold given aircraft pitch and roll attitudes sufficiently long to appreciate the fact that trim attitudes could be maintained with the stick centered. Also, the UARL study was conducted without stick centering forces and small offsets from the stick null position resulted in attitude errors when the pilots attention was diverted elsewhere. Finally, it should be noted that the dynamic response portion of MIL-F-83300 (paragraph 3.2.2.1) which stipulates the pitch and roll dynamics necessary for satisfactory flying qualities does not apply to rate-command/attitude-hold control. This paragraph excludes pitch and roll dynamics having an aperiodic root at the origin and admits oscillatory dynamics with $\zeta = 0.3$, providing ω_n is ≥ 1.1 rad/sec. The data from the UARL study show that rate-command/attitude-hold systems are acceptable, although they have an aperiodic root at the origin. However for them to be acceptable, their ω_n must be much greater than 1.1 rad/sec if ζ is only 0.3. Of course, it was not intended that MIL-F-83300 should necessarily apply to rate-command/attitude-hold systems.

b. Control Sensitivities

Longitudinal and lateral control sensitivities from the rate-command/attitude-hold study are shown in Fig. 29. The control sensitivities increase with ω_n but do not show well-defined trends with ζ . The increases in M_{δ_e} and L_{δ_a} with ω_n are to be expected, since larger sensitivities are needed to offset the restoring moments resulting from this large "spring constant". Upper and lower boundary values for control sensitivity, computed from the MIL-F-83300 requirements for control response, are shown in Fig. 29. Two sets of boundary levels, corresponding to two different values of ω_n , are shown for each of the configurations (BC1 and BC4) evaluated. All of the sensitivities affected by the boundary limits shown lie within the acceptable region.

8. Effect of Motion on Pilot Ratings for Longitudinal and Lateral Control

The results of a comparison of pilot ratings for longitudinal and lateral control from moving-base (MB) and fixed-base (FB) evaluations of identical test cases are summarized in Table XI. There the FB-ratings for the different test cases are categorized according to rating level, i.e., satisfactory, unsatisfactory, and unacceptable. The associated MB ratings for the test cases in a given FB rating category are then listed according to whether the MB ratings were better than, equal to, or worse than the corresponding FB rating. The moving-base ratings were consistently no better than, and generally worse than, the fixed-base ratings for the same test

cases. This trend holds for all three of the FB rating categories. Relatively high frequency pitch and roll control inputs must generally be used to control longitudinal and lateral position properly. There may have been a tendency for the pilots to make more abrupt control commands and also to tolerate disagreeable attitude motions (observed on the visual display) more for fixed-base operation. The addition of motion would have made the pilot more aware of undesirable characteristics in test case dynamic responses. This effect could have overshadowed the benefits of added control cues through motion and caused the poorer moving-base ratings.

TABLE XI
EFFECT OF MOTION CUES ON PILOT RATINGS
FOR LONGITUDINAL AND LATERAL CONTROL

| Fixed-Base (FB) Rating-Level, Number of Ratings | Corresponding Moving-Base Rating | | |
|---|--|--|---|
| | Better than FB Number/Percent of Total | Equal FB Number/Percent of Total | Worse than FB Number/Percent of Total |
| Satisfactory, 18 | 4/22 | 3/17 | 11/61 |
| Unsatisfactory, 20 | 7/35 | 1/5 | 12/60 |
| Unacceptable, 6 | 1/17 | 4/66 | 1/17 |

B. Control-Moment Usage

The discussion of the control-moment usage data is presented in four parts. In part 1 the effects of a number of aircraft, control system and task parameters on pitch, roll and simultaneous pitch and roll control-moment usage (as defined by the moment levels exceeded 5 percent of the time) are described. These results were obtained from experiments in which essentially unlimited control moment was available to the pilot. Specifically, the effects of turbulence intensity, aircraft speed stability and drag parameters, flying qualities level, control system lags, motion coupling, and subtask are described. A comparison is also shown between actual simultaneous pitch- and roll-control-moment usage and hypothetical maxima and minima for such simultaneous usage. These results provide insight into the degree to which pilots make simultaneous control commands. In part 2 results from the study of control-moment limits are discussed. The percent time that total control-moment commands exceeded the installed limits are presented

and correlated with the pilot acceptance of the limits. Parts 3 and 4 are concerned with control-moment usage results for the unconventional control systems considered: independent thrust-vector control and rate-command/attitude-hold control, respectively.

In general, comparisons with the MIL-F-83300 specification for control moments are not made in the discussions of control-moment usage. There are two reasons for this: (1) control-moment comparisons were already made in the discussion of the flying qualities results for the control-moment limits study (Section III.A.3) and, (2) the control-moment usage data are described in terms of the 5-percent-exceedance levels which were shown to be lower than the control-moment limits required for pilot acceptance (Section III.A.3). However, the 5-percent-exceedance levels do provide a useful measure for evaluating control-moment usage (see Section II.D.1.b.). Additional control moment usage data are shown in Appendix E. Exceedance plots based on control moment usage in the maneuvering subtasks are presented there which further illustrate the effects of a variety of aircraft and control system parameters.

1. Effects of Aircraft, Conventional Control System and Task Parameters on Control-Moment Usage

- a. Turbulence Intensity

The effects of turbulence intensity ($\sigma_{u_g} = \sigma_{v_g}$) are presented in Figs. 30 and 31 and also listed in Table C-I in Appendix C. The data in Fig. 30 are for configuration BC1 which requires little pilot compensation or "lead" (Level 1) and is relatively unresponsive to turbulence. That is, the configuration has a relatively high level of stability augmentation ($M_q = L_p = -1.7$ and $M_\theta = L_\phi = -4.2$) and the stability derivatives which describe the moments and forces caused by turbulence, speed stability and drag parameters, respectively, are small ($M_{u_g} = -L_{v_g} = 0.33$, $X_u = Y_v = -0.05$). Figure 31 presents results for configuration BC6 which is Level 2, and more responsive to gusts ($M_{u_g} = -L_{v_g} = 1.0$, $X_u = Y_v = -0.20$).

For configuration BC1 (Fig. 30) the moment levels corresponding to the 5-percent exceedance level generally increase with turbulence intensity for all tasks, although there is appreciable scatter in the results. Also, none of the 5-percent moment levels (pitch, roll, or combined) scale linearly with turbulence. That is, there is a factor of about 2.4 increase in rms turbulence intensity from 3.4 ft/sec to 8.2 ft/sec but the 5-percent control-moment levels at 8.2 ft/sec are not 2.4 times as great as those for 3.4 ft/sec. The reason the control-moment levels do not scale may be that the control inputs necessary for task performance and the pilot's inadvertent inputs form a bias 5-percent moment level upon which the turbulence

effects are superimposed. Of course, the 5-percent moment level for pitch has an additional bias due to the 10 kt mean wind acting through M_u . This bias moment is approximately 0.18 rad/sec^2 .

The levels for configuration BC6 (Fig. 31) are significantly larger than those for BC1. This is to be expected because of the greater response of BC6 to gusts, maneuvering airspeeds and the mean wind. For example, the bias moment in pitch for BC6 due to the mean wind is approximately 0.53 rad/sec^2 . The 5-percent roll control-moment levels for BC6 are generally somewhat smaller than those for pitch, probably also because of the increased bias moment in pitch from the mean wind. In addition, the roll moment levels for BC6 show more of a tendency to scale with turbulence than those for configuration BC1. Turbulence has a greater effect on control-moment requirements for BC6 than BC1 because of the greater response of BC6 to gusts. Consequently, it might be expected that in the absence of significant mean-wind effects, as is the case for roll, the control-moment levels for BC6 would exhibit a greater tendency to scale with turbulence.

b. Speed-Stability Parameter

In Fig. 32 and Table C-1 in Appendix C, control-moment results are presented for configurations BC5 and BC4 which show the effects of aircraft speed stability (M_{ug} , L_{vg}). Both of these configurations have sufficient stability augmentation to yield Level 1 flying qualities and each has drag parameters of $X_u = Y_v = -0.2$ per sec. Their speed-stability parameters differ by a factor of three, however ($M_{ug} = -L_{vg} = 0.33$ for BC5 and 1.0 for BC4). The levels in Fig. 32 show an appreciable increase with speed stability for all three control-moment categories. For the individual-axis control moments the increment due to increased speed stability is greater for pitch where the effects of the mean wind are significant. Also, for none of the moment categories does the change in the 5-percent exceedance level scale directly with the factor of three change in speed stability. This would tend to indicate that the control-moment levels required to arrest and initiate position rates and those caused by random pilot inputs are appreciable. If they were not, we might expect 5-percent levels to scale with speed stability because the remaining disturbance moments due to maneuvering airspeed, the mean wind and turbulence all scale with speed stability. It is interesting to note here, also, that MIL-F-83300 accounts, to an appreciable extent, for the effects of speed stability on required control moments. This is accomplished by stating that the required aircraft response must be demonstrated at the airspeeds involved in task performance (paragraph 3.2.3.1, Ref. 1). Also, in the control-moment limit study the specification was found to be adequate for configurations having both large ($M_{ug} = -L_{vg} = 1.0$) and small ($M_{ug} = -L_{vg} = 0.33$) speed-stability parameters (Section III.A.3).

c. Drag Parameter

The change in the reference control-moment levels with drag parameter (X_u , Y_v) are shown in Fig. 33 and Table C-I in Appendix C. Configurations BC1 and BC5 are identical except that the drag parameters for BC5 are four times those for BC1 (-0.20 versus -0.05). The results in Fig. 33 show a small general increase in the levels for configuration BC5 which has the larger drag parameters. Increased drag parameters result in larger position disturbances from turbulence. However, maneuvering position rates are generally smaller because of the larger drag forces and these rates are easier to arrest because of the increased position damping. The increased disturbances due to turbulence would probably necessitate larger control-moment levels while the other effects of drag parameter should not increase, and could reduce, the required control levels. That is, the attitude angles and rates-of-change need not be as great to arrest position rates for configurations with larger drag parameters. It appears then, from the results in Fig. 33, that the effects of turbulence may have been dominant since the 5-percent levels increased slightly with drag parameter. The increase would appear to be relatively small, however, for a large change in drag parameter. Certainly, the effects of changes in drag parameter are less than those for the changes in speed-stability parameter that were examined.

d. Level of Flying Qualities

The V/STOL Flying Qualities Specification (MIL-F-83300, Ref. 1) defines three flying qualities levels. Level 1 flying qualities are "clearly adequate for the mission," Level 3 are such that the "aircraft can be controlled safely but pilot workload is excessive or mission effectiveness is inadequate, or both" and Level 2 flying qualities lie between these extremes. The control-moment usage data observed for configurations with Level 1, Level 2, and Level 3 dynamic characteristics are shown on Fig. 34. Results are presented there (and also in Table C-I in Appendix C) for configurations BC4, BC2, and EC3 (Level 1, 2, and 3 configurations, respectively), which have identical speed-stability parameters ($M_{u\dot{g}} = -L_{v\dot{g}} = 1.0$). The drag parameters are not identical for each configuration, but drag parameter has a much smaller effect on the 5-percent control-moment level (Fig. 33). There is a general increase in these exceedance moment levels for configurations which fall into the three flying qualities levels of paragraph 3.2.2 in Ref. 1 (Fig. 34) for all three moment categories. That is, as the flying qualities are degraded through reductions in stability augmentation, the control moments used increase. This would indicate that stability augmentation does a more efficient job of compensating the aircraft dynamics and attenuating turbulence inputs than does the pilot. It would appear also that the required levels of installed control moments are decreased with improved aircraft flying qualities.

e. Control System Lags

Control lags appeared to have little effect on control-moment usage. Five percent moment levels for configurations having control system lags are shown in Figs. 35 and 36 (configurations BC5 and BC4, respectively). These data are also summarized in Table C-II in Appendix C. The addition of control lags to BC5, which is Level 1 and has low turbulence response, resulted in a small decrease in the 5-percent levels for pitch and combined control-moment usage, but the levels for roll do not show a consistent change. The effects of control lag on the 5-percent levels for configuration BC4 (Fig. 36) are even less consistent than those for BC5. Configuration BC4 is also Level 1 but more responsive to turbulence than BC5.

f. Inter-Axis Motion Coupling

The effects of both rate and control coupling on the pitch moment levels exceeded 5 percent of the time for configuration BC1 can be seen in Fig. 37 and Table C-IV in Appendix C. Control coupling ($M_{\delta a}/L_{\delta a} = L_{\delta e}/M_{\delta e}$) is treated as a parameter in the three plots of Fig. 37 which correspond to different rate-coupling levels ($M_p = -L_q$). The effects of control coupling alone are shown in Fig. 37(a) where $M_p = -L_q = 0$. These data indicate no significant increase in M_{c5} for a change in control coupling ratios from 0 to $M_{\delta a}/L_{\delta a} = -L_{\delta e}/M_{\delta e} = 0.5$. Recall that for satisfactory pilot ratings control coupling ratios should be kept below 0.25 (Section III.A.5). Consequently, the results in Fig. 37(a) indicate that for acceptable levels of control coupling, the control-moment usage is not changed significantly from that for no control coupling.

However, the results in Fig. 37 show that rate coupling does influence control-moment usage. By comparing the fixed-base data for no control coupling across Figs. 37(a), (b), and (c), it can be seen that pitch control-moment usage increases with rate coupling level. Rate coupling levels greater than $M_p = -L_q = 1$ appear to be unacceptable if satisfactory flying qualities are to be achieved (Section III.A.4). The results in Fig. 37 would indicate that such rate-coupling levels could result in approximately a 10-percent increase control-moment usage.

g. Subtask

Four major subtasks were performed by each pilot during the control-moment-usage study --- maneuvering or air taxi, quick stop, turn-over-a-spot and hover. Two of these, the maneuver and quick-stop subtasks, could be further subdivided according to the direction (longitudinal or lateral) in which the subtask was performed. The effects of each subtask on the 5-percent control-moment-usage level can be seen in Fig. 38 and Table C-I in Appendix C. These data were all obtained for the 3.4 ft/sec turbulence

intensity level and with the 10-kt mean wind from the north. Note that the aircraft was always headed into the wind except for the turn maneuver.

The subtask for which the pitch and roll 5-percent exceedance level was most often the largest was the quick stop (Fig. 38); the next largest values were for the maneuvering subtask. The lowest levels (pitch and roll) were most often recorded for hover and the next lowest for the turn subtask. The quick stops involve somewhat larger maneuver rates than air taxi and these rates are arrested abruptly. Consequently, it is not surprising that the largest control moments were used there. Hover, on the other hand, generally requires smaller control inputs and the pilots tended to make fewer inadvertent inputs for this subtask. This was generally the situation for turn as well, except that the pilots at times introduced large pitch and roll attitudes for lightly damped configurations, e.g., BC2 and BC3.

The combined control-moment-usage levels are shown with the maneuver and quick-stop subtasks divided into their longitudinal (x) and lateral (y) components. The lateral quick stops resulted in the largest 5-percent-exceedance levels for combined usage and the next largest levels were used for the lateral maneuvers. The combined usage for lateral maneuvering and quick stops may have been larger than that for the same longitudinal subtasks because the lateral subtasks required appreciable control moments while pitch moments were also necessary to compensate for the mean wind. For the longitudinal subtasks pitch moments were needed to perform the maneuvers in the mean wind but roll inputs were small. The lowest levels for simultaneous usage were recorded for the hover task.

h. Simultaneous Usage

An indication of the pilot's tendency to make pitch and roll control inputs simultaneously can be obtained by comparing the sum of the moment levels used for the individual axes with the actual simultaneous usage levels. If the 5-percent-exceedance moment levels for pitch and roll are added, the resulting control moment is that level which would be exceeded 5 percent of the time if the pitch and roll control moments were used simultaneously. The sum of these levels then represents a theoretical maximum for simultaneous moment usage. Also, a practical minimum level for combined usage can be developed if it is assumed that the pitch and roll inputs are independent, i.e., that the pilot does not intentionally correlate his pitch (roll) inputs with the roll (pitch) control motions.

Curves representing the hypothetical maxima and minima for the simultaneous control usage 5-percent exceedance level are shown in Fig. 39 along with the 5-percent moment levels for actual simultaneous usage. The results presented for all six configurations are for the hover subtask only (Table C-I in Appendix C). Similar data were not available in sufficient quantity

for the other subtasks. The levels representing the upper curve indicate the 5-percent moment levels which would occur if all the pilot's pitch and roll inputs were made simultaneously. The points on the lower curve are the square root of the appropriate sum of the squared 5-percent levels for pitch and roll. That is, it was assumed that the pitch and roll control moments were independent and could be represented by Gaussian probability distributions (the nearly linear curve for hover in Fig. 5 indicates that the Gaussian assumption is reasonable). It can be shown, then, that the square root of the sum of the squares of the individual 5-percent levels represents the simultaneous usage 5-percent level. The remaining curve in Fig. 39 shows the 5-percent levels for actual simultaneous control usage. This curve lies about midway between the two extremes. These results would indicate that, for the hover subtask at least, the minimum total installed control moment for both pitch and roll could be set somewhat less than the sum of the maximum used for individual axis control. However, this total level must still be greater than a level which would be satisfactory for single-axis control.

2. Percent Time Control Moment Commands Exceed Limits

The control-moment limit study (Section III.A.3) was conducted to determine (1) acceptable levels of installed moments for several V/STOL configurations (BC1, BC4, BC5 and BC6) and (2) whether these limits correlated with the 5 percent exceedance levels measured with unlimited control moments. It was found in that study that control moments greater than the 5-percent levels were needed for pilot acceptance. The results presented here give some indication of the acceptability of installed control moments in terms of the percent time the total control command actually exceeds these limits.

Figure 40 contains plots of the percent time total pitch and roll control commands exceeded the installed moments during the maneuvering subtask versus the magnitude of the installed moments (Table C-III in Appendix C). These maximum available control moments, CM_m , are stated as multiples of the average moment levels exceeded 5 percent of the time with unlimited available moments, CM_5 . Note that CM_5 is different for each basic configuration. As would be expected, the percent time the total moment command exceeded the installed moments decreased as CM_m became larger. However, the exceedance percentages become very small as CM_m approaches those levels needed for pilot acceptance ($CM_m \approx 1.2$ to $1.3 CM_5$ for BC1, $\approx 1.0 CM_5$ for BC5 and ≈ 1.2 to $1.3 CM_5$ for BC4 and BC6). For pitch control the exceedance percentages at acceptable CM_m range from about 1.5 percent (average fixed- and moving-base results for BC1) down to almost zero. For roll control the percentages are about the same magnitude. It would appear from these limited results that for pilot acceptability, installed control moments must be set at levels which will not be exceeded often in flight.

3. Control-Moment Usage for Independent Thrust-Vector Control

Independent thrust-vector control might be expected to reduce the requirements for control moments since it eliminates the need to change attitude in order to maneuver the aircraft. However, control moments are still required to attenuate the attitude response to gusts and trim the moments due to airspeeds (developed from maneuvers and the mean wind) acting on the speed-stability parameters. Pitch control-moment- and thrust-vector-angle-usage data are listed in Table C-V in Appendix C.

In Fig. 41 the pitch and control-moment 5-percent exceedance levels for ITVC and conventional pitch attitude control are presented for configurations BC1 and BC4. For both configurations the value of M_{C5} for ITVC is consistently somewhat smaller than that for conventional attitude control.

Exceedance computations were also performed on measured thrust-vector-angle data from the study of ITVC (Table C-V in Appendix C). For the turn maneuver with configuration BC1 the 5-percent thrust-vector-angle exceedance levels ranged from approximately 2 to 8 deg.

4. Control-Moment Usage for Rate-Command/Attitude-Hold Control

Pitch control-moment-usage results for the rate-command/attitude-hold control system are shown in Fig. 42 for three values of the natural frequency of the oscillatory dynamics ($\omega_n = 2.8, 3.44$ and 6.3 rad/sec) and several levels of the damping ratio, ζ . These data are presented for test cases having the basic airframe stability derivatives of configuration BC1. As the damping ratio was increased for both $\omega_n = 2.8$ and 6.3 rad/sec, the configuration became easier to control and the 5-percent exceedance moment level decreased. However, for the two test cases yielding the best fixed-base ratings ($\omega_n = 3.44$, $\zeta = 0.87$, PR = 4 and $\omega_n = 6.3$, $\zeta = 0.47$, PR = 2.5) the fixed-base 5-percent moment usage levels were still greater than the corresponding levels for BC1 with conventional attitude control (see Fig. 41).

SECTION IV

RESULTS OF HEIGHT CONTROL STUDIES

The height control results are discussed in two parts. In part A, the flying qualities data, i.e., pilot opinion ratings and control sensitivities, are discussed and compared with the applicable paragraphs of MIL-F-83300. In part B, the measured thrust-usage data are described. Background material on the experimental design and procedures are contained in Section II. The flying qualities data, pilot comments and measured thrust-usage results from the UARL pilot evaluations are summarized in Appendices A, B and C, respectively. Results from the Calspan pilot evaluations discussed in this section are summarized in Appendix D.

A. Flying Qualities Results

Four separate investigations were conducted during the height control study. These investigations were concerned with (1) the effects of height velocity damping with effectively unlimited thrust-to-weight ratio, (2) the interaction between height velocity damping and thrust-to-weight ratio, (3) lags and delays in the thrust response, and (4) incremental thrust through stored energy.

1. Height Velocity Damping

a. Pilot Opinion Ratings

The effects of height velocity damping, Z_w , on pilot opinion for effectively unlimited thrust-to-weight ratio, $T/W > 1.15$, are presented in Fig. 43 and summarized in Table A-IX (Cases HZ1 through HZ4 and HZ25 through HZ28). Data are shown in Fig. 43 for one Calspan pilot and two UARL pilots. The Calspan pilot evaluations were conducted with no simulated winds and with the simulator in the moving-base mode, while the UARL pilot results were obtained for fixed- and moving-base simulator operation and the standard wind simulation (10-kt mean wind from the north and 3.4 ft/sec gusts along the aircraft x and y body axes). The configurations simulated during these evaluations were BC1 and BC4 which both have Level 1 longitudinal and lateral flying qualities. The ratings from all three pilots are unsatisfactory (and quite similar) for less damping than about $Z_w = -0.35$ per sec. For $Z_w = 0$ the ratings ranged from 8 to 10 and the pilots all commented that stabilizing aircraft vertical motion was extremely difficult. They also indicated that it would probably be impossible to perform any other task, such as a lateral air taxi, in addition to controlling height (see Appendix B, Table B-VIII). The improvement in rating with increased levels of height velocity damping correlates well with the associated reduction in

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requirements for pilot lead compensation. The phase lags in the height response to height errors are shown in Fig. 44. Pilots must compensate for these lags at frequencies important to closed-loop height control (0.5 to 1.0 rad/sec; Ref. 7). It is apparent in Fig. 44 that the lead requirements diminish with additional Z_w .

The specification for minimum height velocity damping (paragraph 3.2.5.4) indicates that, for effectively unlimited T/W ($T/W \geq 1.10$), satisfactory height control characteristics can be obtained with $Z_w = 0$. The results in Fig. 43 indicate that the flying qualities are unacceptable without height velocity damping. If the pilot's only task were to control height he may be able to stabilize the altitude loop with $Z_w = 0$. However, the UARL results indicate that if he is also expected to perform tasks involving longitudinal, lateral or directional motion, altitude errors of at least ± 20 ft could be expected. In addition, the precision with which the other tasks could be performed would be seriously degraded by the attention which would have to be given to height control.

b. Collective Control Sensitivities

Pilot-selected control sensitivities from the investigation of height velocity damping are shown in Fig. 45. The sensitivities change little with Z_w although there is a tendency for them to become larger as damping is increased. The minimum permissible MIL-F-83300 boundaries for collective control sensitivity are also plotted in Fig. 45. These boundaries are stated in terms of achieving a climb rate of 100 ft/min 1.0 sec after an abrupt 1-in. control input. Consequently, the boundaries increase as the damping is increased. The control sensitivities from this study all lie well within the allowable range, but they are much closer to the minimum boundary than the maximum. The maximum permissible collective control sensitivities range from $Z_{\delta c} = 12.5$ to 18.1 as Z_w changes from 0 to -0.8.

2. Interaction Between Height Velocity Damping and Thrust-to-Weight Ratio

Figure 46 contains results which demonstrate the interaction between Z_w , T/W and pilot ratings. These data are also listed in Table A-IX, Cases HZ1 through HZ28. In Fig. 46 pilot ratings are presented on a plot of total height velocity damping, Z_{wT} , versus T/W. Similar plots of the results from other height control studies were used to formulate height control power requirements for MIL-F-83300. The data on Fig. 46 were obtained for UARL and Calspan pilots and for fixed- and moving-base flight simulator operation. The basic configuration evaluated was BCL. For most of the data points, Z_{wT} consisted of equal parts of aerodynamic (Z_{wA}) and SAS (Z_{wS}) height velocity damping. However, as indicated in Fig. 46 some of the cases were evaluated with either Z_{wA} or Z_{wS} (but not both) set to

zero. It should be noted that Z_{WS} is provided only within the available T/W. That is, thrust used for damping is instantaneously unavailable for control. Also shown in Fig. 46 are Level 1, 2 and 3 boundaries for height control power from MIL-F-83300.

A definite trade off between the effects of T/W and Z_{WT} on pilot opinion is indicated by the results in Fig. 46. For example, as T/W is increased at constant Z_{WT} , ratings generally improve. Conversely, as the damping is increased for a given T/W, rating also generally improves. These effects tend to justify, to some extent, the shape of the MIL-F-83300 boundaries. However, the data in Fig. 46 are not in complete agreement with these boundaries. One notable exception occurs for the Level 1 boundary at T/W = 1.10 where the UARL results would indicate that total damping greater than -0.25 is necessary for satisfactory ratings. That is, the boundaries in Fig. 46 imply that a T/W > 1.10 is required for a satisfactory rating at $Z_{WT} = 0$. However, the results shown previously in Fig. 45 indicate that even an "unlimited" T/W will not provide satisfactory ratings for $Z_{WT} = 0$. The UARL data would indicate, then, that another boundary line which excludes damping levels smaller than -0.25 should be added to Fig. 46. If this boundary were present the UARL data would also support the movement of the line separating Level 1 and 2 regions to the left. That is, it appears that for a given Z_{WT} less T/W is needed to place a configuration in a Level 1 category than MIL-F-83300 requires.

The interaction between aerodynamic, Z_{WA} , and SAS, Z_{WS} , height velocity damping shown in Fig. 46 merits discussion. A decelerating force which is proportional to descent velocity is available to arrest sink rates in aircraft which have Z_{WA} . Such force may have an appreciable effect on height control for aircraft with limited installed T/W. This increased decelerating force is not available in aircraft with only Z_{WS} . Ratings showing the effects of Z_{WA} and Z_{WS} , with T/W as a parameter, are presented in Fig. 47. For all the cases shown, the total damping was $Z_{WT} = -0.25$, but the relative amounts of Z_{WA} and Z_{WS} were varied. For T/W = 1.02 it appears that the improved ability to arrest sink rates resulting from increased Z_{WA} had a significant impact on flying qualities. As Z_{WA} was changed from 0 to -0.25, pilot rating improved by two units. As T/W was increased the decelerating force from Z_{WA} became less important since the pilot had sufficient T/W to adequately ascend and arrest descents. This is reflected in the smaller change in rating over the same Z_{WA} interval for the larger T/W values. In fact, the moving-base ratings for T/W = 1.10 show almost no variation with Z_{WA} .

3. Lags and Delays in Thrust Response

The effects on pilot rating of first-order lags and a 0.1-sec delay in the thrust response are presented in Fig. 48 and Table A-X (Cases H11 through

HL8). Two values of lag time constant, $\tau_h = 0.3$ and 0.6 sec were evaluated at three levels of Z_{WT} : -0.25 , -0.35 and -0.50 . The thrust-to-weight ratio was held constant at 1.05 and configuration BCL was used for the longitudinal and lateral flying qualities. Except for $Z_{WT} = -0.50$, rating deteriorates with increasing τ_h . The decrement appears to be related to Z_{WT} as well as the change in τ_h (Fig. 48). That is, rating is somewhat less sensitive to τ_h for the higher damping levels. The upward shift in the curves with Z_{WT} is expected since the phase lag in height response at any given τ_h , and hence the pilot's lead compensation, decreases with increasing damping (see Fig. 44). Note also, that the addition of a 0.1 -sec delay had little effect on rating (Fig. 48). Pilot rating for $Z_{WT} = -0.35$ with $d_h = 0.1$ sec and $\tau_h = 0$ is equal to that for no delay, and for $\tau_h = 0.3$ the rating with a 0.1 -sec delay is only a half unit poorer than for no delay.

The specification for lags in thrust response (paragraph 3.2.5.2) is phrased in such a way that, with no delays, a first-order control lag time constant of up to 0.3 sec is permissible. For a $d_h = 0.1$ the specification would permit a lag of $\tau_h \approx 0.2$ sec. The UARL data in Fig. 48 would indicate that the specification is reasonable, providing the aircraft has a Z_{WT} of at least -0.25 to -0.35 per sec. This is the range of minimum values of damping found to be acceptable in the height control studies with no lags. The previous results (e.g., Fig. 43) would indicate that for $Z_{WT} = 0$, $\tau_h = 0.3$ would be completely unacceptable. Also, the specification does not account for the reduction in phase lags contributed by τ_h or d_h , and the associated improvement in rating, which can be achieved with increased levels of Z_{WT} . This effect is illustrated in Fig. 48 and is discussed in detail in Ref. 7.

4. Incremental Thrust Through Stored Energy

The effects of incremental thrust through stored energy (see Section II.A.2.d for background) were investigated with a height control configuration that was unsatisfactory without the stored energy contribution. However, the longitudinal and lateral dynamics were quite easy to control (configuration BCL). For height control the installed T/W was only 1.02 and $Z_{WT} = Z_{WS} = -0.35$, i.e., the pilot had no additional decelerating force from Z_{WA} when descending. Without the incremental thrust from stored energy, height control was unsatisfactory ($PR = 4$). The change in rating was evaluated for incremental thrust-to-weight ratios of $\Delta T/W = 0.13$ and 0.28 and for decay time constants of $\tau_A = 0.05$, 0.10 and 0.20 sec (Cases HS1 through HS5, Table A-X). With $\Delta T/W = 0.13$, an improvement in rating was not evident until $\tau_A = 0.20$ (Fig. 49). For the larger thrust increment, $\Delta T/W = 0.28$, a general improvement in rating occurred for $\tau_A = 0.10$ sec. For both the $\Delta T/W = 0.13$, $\tau_A = 0.20$ and $\Delta T/W = 0.28$, $\tau_A = 0.10$ combinations, the ratings improved by about one unit to $PR = 3.0$. For effectively unlimited T/W, the rating was 2.5 . The results indicate that for τ_A values which might be typical for helicopters, i.e., $\tau_A = 0.10$ to 0.20 sec, the effects of incremental thrust

through stored energy can be significant. It should be noted, also, that for height control the pilot probably does not use the stored energy effects to their fullest advantage. Height control generally involves low-frequency control motions; consequently, the stored energy in the rotor system is not used as often as it is for pitch and roll control.

5. Effect of Motion and Pilot Ratings for Height Control

Fixed-base (FB) and moving-base (MB) pilot ratings for height control are compared in Table XII. The FB ratings for the different test cases are categorized by general rating level (satisfactory, unsatisfactory and unacceptable). The associated MB ratings are then tabulated according to whether they were better than, equal to, or worse than the FB ratings. The results in Table XII are mixed and only for the unsatisfactory FB rating

TABLE XII

EFFECT OF MOTION CUES ON PILOT
RATINGS FOR HEIGHT CONTROL

| Fixed-Base (FB) Rating Level, Number of Ratings | Corresponding Moving-Base Rating | | |
|---|--|--|---|
| | Better Than FB Number/Percent of Total | Equal FB Number/Percent of Total | Worse Than FB Number/Percent of Total |
| Satisfactory, 4 | 1/25 | 1/25 | 2/50 |
| Unsatisfactory, 7 | 5/72 | 1/14 | 1/14 |
| Unacceptable, 2 | 0/0 | 2/100 | 0/0 |

category is a definite result indicated. For this category the moving-base ratings were generally better than the corresponding fixed-base data. It would appear that motion helped in the control of these more difficult test cases. It may be that the motion was more beneficial for height control than for longitudinal and lateral control because the visual display provides less information on height error than it does for these other two axes.

Consequently, motion cues would have helped more for height control. This effect may not have been evident for unacceptable FB ratings because the rating scale becomes less sensitive to such effects due to its implicit nonlinearities for the unacceptable region. That is, for test cases which are very difficult to control the differences between 7 and 8 or 8 and 9 ratings are not easy to establish and pilots tend to rate such cases similarly.

B. Thrust Usage

Thrust-usage data were obtained which show (1) the effects of Z_H , (2) the percent time that pilots attempted to exceed the installed thrust-to-weight ratio, and (3) the effects of lags. The thrust exceedance results were computed using only the pilot and total thrust commands for which $T/W > 1$. These are the collective inputs which are used to accelerate upward and to arrest sink rates. Also, thrust usage levels are given in terms of incremental thrust-to-weight ratio, i.e., $(T/W - 1)$.

1. Height Velocity Damping

The effects of total height velocity damping, Z_{WTP} , on the level of incremental thrust-to-weight ratio exceeded 5 percent of the time are shown in Fig. 50 and listed in Table C-VII. Results are shown for both the collective command, $Z_{\delta C} \cdot \delta_C$, and the total thrust command, $Z_{\delta C} \cdot \delta_C + Z_{WS} \cdot w$. Three levels of Z_{WTP} (0, -0.25 and -0.5 per sec) were evaluated for effectively unlimited T/W ($T/W > 1.15$). The data in Fig. 50 show that Z_{WTP} has a significant effect on the 5-percent exceedance level, $(T/W - 1)_5$. The 5-percent level for $Z_{WTP} = 0$ is as much as six times that for Z_{WTP} of -0.25 or -0.5. Obviously, the stability augmentation system makes much more efficient use of the installed thrust than the pilot. Also, there generally seems to be little difference between the exceedance levels for $Z_{WTP} = -0.25$ and -0.50. It would appear that increasing Z_{WTP} above what is a minimum satisfactory level (e.g., $Z_{WTP} \sim -0.25$) does not lead to significant changes in thrust usage. Note also that for relatively well damped cases, $Z_{WTP} = -0.25$ and -0.50, the largest thrust levels are used for the landing sequence. This is to be expected, since for this subtask the pilot intentionally makes several large altitude changes. For $Z_{WTP} = 0$, however, large thrust levels are used for other subtasks in which the pilot is merely attempting to maintain constant altitude. Normally, large values of $(T/W - 1)$ are not needed for such control if the height dynamics are acceptable to the pilot.

2. Limits on the Installed Thrust-to-Weight Ratio

The effects of limits on the installed thrust-to-weight ratio are discussed in terms of the percent time pilots attempted to exceed the incremental T/W available. The collective control was not physically constrained at the thrust limits for this study. The thrust limits were evident only in the way they affected height control. Consequently, if the pilot felt he

needed more thrust, he tended to move the collective lever accordingly, whether or not the installed T/W had been exceeded. Results are presented in Fig. 51 for two levels of Z_{WT} (-0.25 and -0.50) with T/W as a parameter. For $Z_{WT} = -0.25$ (note that $\tau_h = 0.3$ for the $T/W = 1.05$ data) the two types of commanded thrust, $Z_{\delta_C} \cdot \delta_C$ and $Z_{\delta_C} \cdot \delta_C + Z_{WS} \cdot w$, both exceeded the $T/W = 1.02$ level a large percent of the time. Fifty percent was not uncommon for $Z_{\delta_C} \cdot \delta_C$ and 20 percent was typical for the total commanded thrust. However, the percentages for $T/W = 1.05$ were much smaller. More often than not, the $T/W = 1.05$ level was never exceeded. The results for $Z_{WT} = -0.50$ show the same trends, but the percent time a given level is exceeded is smaller. For example, the maximum percent time that $T/W = 1.02$ was exceeded for any subtask was 30 percent. Also, the only time that $T/W = 1.05$ was exceeded was for the landing sequence and the percentage there was relatively low. These results provide another example of SAS making more efficient use of thrust than the pilot.

3. Thrust Response Lags

Some limited data showing the effects of an acceptable first-order lag in thrust response ($\tau_h = 0.3$) are presented in Fig. 52. For these results Z_{WT} is -0.25 and T/W is 1.10. The 5-percent exceedance levels are generally somewhat larger for $\tau_h = 0.3$ (and appreciably larger for the y-maneuver subtask) than for the no lag case. However, these data are too limited to permit the conclusion that significantly more thrust is needed for height control systems with lags.

SECTION V

RESULTS OF DIRECTIONAL CONTROL STUDIES

The results of the directional control studies are presented in two parts. Pilot ratings and pilot-selected control sensitivities are discussed and compared with applicable paragraphs of MIL-F-83300 in part A. In part B the measured yaw control-moment data are discussed. Background information related to the directional control experiments is contained in Section II. The flying qualities data, pilot comments, and control-moment data are summarized in Appendices A, B and C, respectively.

A. Flying Qualities Results

Three different studies were conducted during the directional control program. These studies consisted of evaluations of the effects of (1) yaw rate damping, (2) control system lags and delays, and (3) limits on yaw control moment.

1. Yaw Rate Damping

Pilot rating is plotted versus yaw rate damping level, N_r , in Fig. 53(a) for configurations BC1 and BC2. Note that these ratings are for directional control only. Three values of N_r (0, -0.5 and -1 per sec) were evaluated at $N_y = 0.005$. Pilot rating was marginally unacceptable (PR ~ 6.5) for $N_r = 0$ and marginally satisfactory (PR = 3.5 to 4) for $N_r = -0.5$. Ratings improved to about 2.5 with $N_r = -1$ for both BC1 and BC2. Recall that BC2 has Level 2 longitudinal and lateral characteristics and such dynamics result in an increase in overall pilot workload. It might have been expected, therefore, that a degradation in pilot rating of the directional flying qualities could result. However, this was not the case. The reason for the improvement in rating with damping level can be interpreted in terms of the pilot lead compensation necessary for good closed-loop directional control characteristics. As for height control, the directional lead compensation requirements are related to the open-loop phase lags of the directional dynamics (and the pilot dynamics) in the frequency range of 0.5 to 1 rad/sec (Ref. 7). These phase lags are shown in Fig. 54. It is apparent that the need for lead compensation is diminished as N_r becomes more negative.

The MIL-F-83300 requirement for directional damping (paragraph 3.2.2.2) states that for Level 1 flying qualities the yaw mode must be stable with a time constant no greater than one sec. This is approximately equivalent to specifying $N_r = -1$ for Level 1 flying qualities and the UARL results in Fig. 53(a) show that satisfactory ratings result for such a value. The data also indicate that a somewhat lower damping level of about -0.5 per sec

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may provide satisfactory directional control for $N_V = 0.005$. However, the value of N_V can be larger than 0.005 for helicopters and V/STOL aircraft. Since directional flying qualities generally deteriorate with increasing N_V (Ref. 7), the $N_r = -1$ Level 1 requirement appears reasonable.

Control sensitivities selected by the pilots during the yaw rate damping study are shown in the following list along with the minimum and maximum values permitted by MIL-F-83300. The UARL data from the two pilots and the moving- and fixed-base evaluations have been averaged.

| N_r | UARL N_{δ_r} | MIL-F-83300 Boundaries for N_{δ_r} | |
|-------|------------------------|--|---------|
| | | Minimum | Maximum |
| 0 | 0.207 | 0.210 | 0.804 |
| -0.5 | 0.236 | 0.244 | 0.935 |
| -1 | 0.299 | 0.282 | 1.080 |

The UARL control sensitivities almost match the lower boundary values from MIL-F-83300 and, consequently, they are well below the upper limits for N_{δ_r} .

2. Control Lags and Delays

First-order lags in yaw response to the pilot's pedal inputs having time constants of $\tau_\psi = 0.1, 0.3$ and 0.6 were evaluated with and without a 0.1-sec time delay. Two values of N_r (-0.5 and -1) were used with configuration BCL providing the longitudinal and lateral dynamics. Pilot ratings from these cases are shown in Fig. 53(b). There is a consistent deterioration in rating with lag time constant for both $N_r = -0.5$ and -1 . Also, the ΔPR due to the different N_r values remains about the same for all τ_ψ , i.e., the ratings for $N_r = -1$ are consistently about 1 unit better. The addition of the 0.1-sec delay did not change the ratings significantly (Fig. 53(b)). The effect of the lags and the different N_r values can once more be rationalized in terms of the required pilot lead compensation. The phase lags encountered in directional control increase with τ_ψ which in turn increases the requirement for pilot lead compensation and this causes pilot rating to deteriorate. Increasing the damping level, N_r , reduces the phase lags and thereby improves the pilot's rating at a given value of τ_ψ .

The results in Fig. 53(b) show that for a Level 1 value of N_r (-1), first-order lags with time constants of up to $\tau_\psi = 0.3$ are acceptable. The

specification for directional control lags (paragraph 3.2.4) is written in terms of an allowable time within which the initial maximum yaw acceleration must occur ($t_{\ddot{\psi}_{\max}} \leq 0.3$ sec). The value of $t_{\ddot{\psi}_{\max}}$ for the lag cases evaluated (with and without $d_{\psi} = 0.1$ sec) with $N_r = -1$ are summarized in the following list.

| N_r | τ_{ψ} | d_{ψ} | $t_{\ddot{\psi}_{\max}}$ | FR |
|-------|---------------|------------|--------------------------|-----|
| -1 | 0.1 | 0 | 0.24 | 3 |
| | | 0.1 | 0.34 | 2 |
| -1 | 0.3 | 0 | 0.51 | 3.5 |
| | | 0.1 | 0.61 | 3.8 |
| -1 | 0.6 | 0 | 0.86 | 4.8 |
| | | 0.1 | 0.96 | 4.7 |

Without delays the specification excludes $\tau_{\psi} = 0.3$ ($t_{\ddot{\psi}_{\max}} = 0.51 > 0.30$) although this test case was rated satisfactory. Also, the specification permits a 0.1-sec delay which the UARL data indicate is reasonable. However, if $d_{\psi} = 0.1$ is present a 0.1-sec increment is added to $t_{\ddot{\psi}_{\max}}$. As a result, some combinations of d_{ψ} and τ_{ψ} which are acceptable to the pilot, e.g., $\tau_{\psi} = 0.3$ and $d_{\psi} = 0.1$ are made to appear even more unacceptable in terms of the MIL-F-83300 requirement. That is, $t_{\ddot{\psi}_{\max}} = 0.61$ for $\tau_{\psi} = 0.3$ and $d_{\psi} = 0.1$ which is twice the allowable $t_{\ddot{\psi}_{\max}}$ value (0.30), yet the averaged rating for this case is almost on the satisfactory boundary (FR = 3.8). The control lag specification (paragraph 3.2.4) assumes that the time to maximum angular acceleration limit of 0.3 sec is applicable to pitch, roll and yaw motion. It was shown previously (Section III.A.2) that this requirement is adequate for first-order lags in pitch and roll response. However, it appears that a longer time to maximum angular acceleration is appropriate for yaw.

3. Control-Moment Limits

Yaw control-moment limits were evaluated to determine acceptable values of installed yaw moment for the UARL task. The total yaw control moment was limited, but pitch and roll control moments were effectively unlimited. This evaluation was conducted for two values of N_r (-0.5 and -1 sec) with configuration BCl. The reference value for yaw moment was the average level exceeded 5 percent of the time for the turn subtasks conducted during the turbulence intensity study ($\bar{N}_{C5} = 0.10$). Note that this value of \bar{N}_{C5} was appropriate only for configuration BCl. Larger values were recorded for other configurations (see Section III.A.3). Pilot ratings from this study are presented in Fig. 55. For the Level 1 value of N_r (-1) an installed yaw control moment of $N_{Cm} \approx 1.3 \bar{N}_{C5}$ was necessary for pilot

acceptance. With $N_x = -0.5$ the required value for N_{cm} was considerably larger ($\approx 1.6 \bar{N}_{C5}$). If nominal lateral maneuvering velocities of 15 ft/sec are assumed, MIL-F-83300 requires that the installed yaw control moment be approximately 0.31 rad/sec². This level is well in excess of the 0.13 rad/sec² found to be necessary with configuration BC1. However, as mentioned previously, the levels of yaw control moment used varied among the different Level 1 configurations ($\bar{N}_{C5} = 0.175$ for BC4 and 0.15 for BC5). If it were assumed that for configuration BC4 the required installed $N_{cm} = 1.3 \bar{N}_{C5}$, then N_{cm} would have to be 0.228 rad/sec². This value is also less than the 0.31 rad/sec² specified by MIL-F-83300.

4. Effect of Motion on Pilot Ratings for Directional Control

Fixed-base (FB) and moving-base (MB) pilot ratings for directional control are compared in Table XIII. The method of comparison is similar to

TABLE XIII

EFFECT OF MOTION CUES ON PILOT RATINGS FOR DIRECTIONAL CONTROL

| Fixed-Base (FB) Rating Level, Number of Ratings | Corresponding Moving-Base Rating | | |
|---|--|--|---|
| | Better Than FB Number/Percent of Total | Equal FB Number/Percent of Total | Worse Than FB Number/Percent of Total |
| Satisfactory, 5 | 2/40 | 1/20 | 2/40 |
| Unsatisfactory, 8 | 5/62.5 | 1/12.5 | 2/25 |
| Unacceptable, 1 | 1/100 | 0/0 | 0/0 |

that described previously for the height control ratings. The effect of motion on the rating results is also quite similar to those for height control. That is, motion had little effect for satisfactory FB ratings, but improved the ratings for test cases which were more difficult to control

(i.e., those which were rated unsatisfactory and unacceptable with no motion). As for height control, the reason for the improved ratings with motion may have been the improved cues which resulted for heading. This effect would be expected to be more significant for heading control than for longitudinal and lateral control. This is because the visual display provides much better control cues for longitudinal and lateral control than for directional control.

B. Control-Moment Usage

Two of the three investigations related to yaw control-moment usage were based on data obtained with unlimited yaw moment available. The effects of N_r and control lags were evaluated in these two studies. The third study was concerned with the percent time the total yaw control command exceeded the installed moment. Only results for the turn subtask were considered in the control-moment-usage investigations. Very little yaw control moment was used for the other subtasks.

1. Yaw Rate Damping

The effects of N_r on the 5-percent yaw moment exceedance levels are displayed in Fig. 56(a). As was the case for pitch, roll and height control, the 5-percent level for yaw moment decreases with increased damping. Again, it is apparent that with increased levels of stability augmentation, more efficient use is made of the available control moments.

2. Control Lags

The percent-time reference yaw moment levels were exceeded was computed from the moment data for $\tau_{\psi} = 0.3$ with $N_r = -0.5$ and for $\tau_{\psi} = 0.3$ and 0.6 with $N_r = -1$. The moment levels exceeded 5 percent of the time are presented in Fig. 56(b). For both levels of N_r there was a significant increase in the 5-percent-exceedance value, N_{c5} , when a first-order lag of 0.3 sec was added to the control system. A further increase in N_{c5} was observed for a lag of 0.6 sec. The increase in N_{c5} is approximately 50 percent for the addition of $\tau_{\psi} = 0.3$ sec with $N_r = -1$. The results in Fig. 53(b) indicate that this combination yields satisfactory flying qualities. If satisfactory levels of control lag can cause this large an increase in the yaw control-moment usage, it would appear prudent not to change the MIL-F-83300 specification for installed yaw moments. Without control lags the MIL-F-83300 requirements appeared somewhat larger than the yaw control moments found necessary for pilot acceptance in the UARL studies (Sections V.A.3 and III.A.3).

3. Control-Moment Limits

The percent time that total yaw control-moment commands exceeded the installed moment limits are shown in Fig. 56(c). These percentages were computed from yaw control-moment-usage data for the moment limit values evaluated in the study discussed in Section V.A.3 ($N_{C_m} = 1.0 \bar{N}_{C_5}$, $1.3 \bar{N}_{C_5}$ and $1.6 \bar{N}_{C_5}$ where $\bar{N}_{C_5} = 0.10$). As would be expected, the percentages decreased as the installed yaw control moment increased. Also, these results show that the yaw control-moment level which was acceptable to the pilots, $N_{C_m} = 1.3 \bar{N}_{C_5}$, was exceeded 5 percent of the time. Recall that the reference, $\bar{N}_{C_5} = 0.10$, was the averaged 5-percent exceedance moment level for all the data measured during the turn subtask in the turbulence study (Section III.A.1), when essentially unlimited control moment was available. The larger 5-percent level from the yaw limit study, $N_{C_m} = 0.13$, may have resulted from the pilot's tendency to hold in large pedal inputs which exceeded the yaw control-moment limits. This was done in an attempt to command increased yaw control moment. For unlimited yaw control moments available the aircraft responded to these large inputs and the pilot did not hold the pedal command as long.

SECTION VI

SUMMARY OF PRINCIPAL RESULTS AND RECOMMENDATIONS FOR FURTHER RESEARCH

A. Flying Qualities Results Pertaining to the Development of MIL-F-83300

1. Longitudinal and Lateral Control

a. Turbulence Effects

The Level 1 requirement for V/STOL pitch, roll and yaw dynamic response (paragraph 3.2.2) appears to provide aircraft dynamics which remain quite controllable for nominal increases in turbulence intensity. Pitch and roll control sensitivities selected by the pilots at the largest turbulence intensities considered ($\sigma_{u_g} = \sigma_{v_g} \approx 8.2$ ft/sec) remained well within the specification boundaries (paragraph 3.2.3.2) and were much closer to the minimum required levels than to the maximum limit. These results and previous UARL experience would indicate that the upper control sensitivity limits would result in aircraft response which might be difficult to control.

b. Control Lags and Delays

The specification for control lags (paragraph 3.2.4) adequately separated unsatisfactory levels of first-order lags in pitch and roll control response from those which did not significantly degrade pilot ratings for Level 1 configurations (i.e., those that met the Level 1 requirement of paragraph 3.2.2 of MIL-F-83300) evaluated in this study. Pilot ratings also show that permitting a 0.1-sec delay in control response, as the specification does, is reasonable. However, limited results for second-order control lags indicate that the specification may not be sufficiently general to apply to second-order control lags. Control sensitivities selected in this study were generally near, and sometimes below, the minimum MIL-F-83300 boundary. It may be appropriate to lower both the minimum and maximum control sensitivity boundaries somewhat.

c. Control-Moment Requirements

The pitch and roll control-moment requirements from MIL-F-83300 (paragraph 3.2.3.1) generally equalled or exceeded those levels found to be necessary in this program for the Level 1 and 2 configurations considered (without control system lags or delays). Also, the specified control moments were generally not excessive. The addition of control system lags and delays increased the control moments found to be necessary for satisfactory ratings, and the wording of paragraph 3.2.3.1 also provides for this effect. However, the specification control-moment requirements may be excessive for control systems with acceptable lags.

d. Control Moments Through Stored Energy

It appears that rotor-propulsion system angular momentum can be used to offset, to some extent, deficiencies in the installed control moments. However, additional research is required before consideration can be given to accounting for its effects in MIL-F-83300.

e. Inter-Axis Motion Coupling

Pitch and roll rate coupling and control coupling can cause an appreciable deterioration in V/STOL flying qualities. Results from this study indicate that rate coupling levels must be no larger than $M_p = 1$ and/or $L_q = -1$ per sec for satisfactory flying qualities. Control coupling ratios should be limited to $M_{\delta a}/L_{\delta a}$ and/or $L_{\delta e}/M_{\delta e}$ less than about 0.25. The control sensitivity specification does not have to be changed to account for motion coupling.

f. Independent Thrust-Vector Control

Thrust-vector control independent of aircraft attitude can be an acceptable substitute for conventional attitude control when properly implemented. For large aircraft with Level 1 pitch and roll dynamics, the use of ITVC should provide satisfactory flying qualities while enabling the pilot to avoid pitch (or roll) attitudes that could lead to ground strikes. For aircraft having large drag parameters, ITVC would enable pilots to control position without the large attitude changes and trim attitude angles that result for such aircraft with conventional position control through attitude. However, position control for such aircraft would remain moderately difficult, even with ITVC.

g. Rate-Command/Attitude-Hold Control

It appears that rate-command/attitude-hold control as mechanized in this study provides no particular benefits over conventional rate and attitude stabilized control systems for hover and low-speed flight operations. Also, the dynamic response portion of MIL-F-83300 (paragraph 3.2.2.1) does not define characteristics which provide satisfactory dynamic response for rate-command/attitude-hold control systems. However, the specification for control sensitivities (paragraph 3.2.3.2) does encompass those sensitivities needed with rate-command/attitude-hold control.

2. Height Control

a. Z_w and Thrust-to-Weight Ratio

There is a definite interaction between Z_w , T/W and height control flying qualities for T/W less than about 1.05. This result supports to

some extent the method used in MIL-F-83300 to specify Z_w and T/W (paragraph 3.2.5.1). However, MIL-F-83300 permits $Z_w = 0$ for $T/W \geq 1.10$, but results from the UARL program indicate that a minimum $Z_w = -0.25$ to -0.35 is necessary for Level 1 height control. Also, if this Z_w level is present, it would appear that the T/W boundary separating Level 1 and 2 flying qualities could be reduced. Height control sensitivities from this study were within the specification limits (paragraph 3.2.5.3) but were much closer to the minimum boundary than the maximum.

b. Lags and Delays in Thrust Response

The specification for lags and delays in thrust response (paragraph 3.2.5.2) appears reasonable in view of the UARL results. However, it does not account for the ability of increased Z_w to compensate for lag effects.

c. Incremental Thrust Through Stored Energy

Results indicate that the effects of incremental thrust through stored energy can alleviate, to an extent, deficiencies in installed thrust. However, these data are presently too limited to permit consideration of changes in MIL-F-83300 to account for its effects.

3. Directional Control

a. Yaw Rate Damping

Results from this program indicate that the directional damping paragraph in MIL-F-83300 (3.2.2.2) which requires $N_r = -1$ for Level 1 flying qualities is reasonable. Also, the pilot-selected yaw control sensitivities, N_{δ_r} , almost matched the lower boundary values from paragraph 3.2.3.2.

b. Control Lags and Delays

The control lag specification (paragraph 3.2.4) should be modified to permit a longer time to attain maximum yaw acceleration, $\ddot{\psi}_{max}$. For acceptable control lags and delays, $\ddot{\psi}_{max}$ was as much as twice the MIL-F-83300 limit (0.3 sec).

c. Yaw Control-Moment Requirements

The specification for yaw control moment (paragraph 3.2.3.1) requires control moments which are without exception larger than those found to be necessary in this program. However, the yaw control-moment requirements of the specification do not appear to be excessive.

B. Control-Moment Usage

1. Longitudinal and Lateral Control

Pitch and roll control-moment usage increases with turbulence intensity. However, the increase does not scale directly with turbulence intensity, apparently because there is a minimum level of control-moment usage which exists without turbulence due to the moment requirement for task performance, trim of the mean wind, and inadvertent pilot inputs. Speed stability is the aircraft/control system configuration parameter having the greatest effect on control-moment usage. The change in the 5-percent-exceedance moment levels for a threefold increase in speed stability was much greater than that for a factor of four change in drag parameter. Drag parameter may not have to be a consideration in the development of control-moment criteria. The change in control-moment usage with speed stability was also greater than that which resulted when aircraft pitch and roll dynamics deteriorated (accomplished by reducing the level of stability augmentation) from Level 1 to Level 3. Control-moment usage increased with decreasing level of augmentation which confirms that stability augmentation systems make more efficient use of control moment than does the pilot. Control lags had little effect on pitch and roll control-moment usage, and it may be possible to eliminate them from consideration in the development of control-moment specifications. Pitch and roll control coupling also had little effect on control-moment usage, but usage did increase with pitch and roll rate coupling.

The low-speed flight task required of a V/STOL aircraft has been shown to have an appreciable effect on control-moment usage. The 5-percent-exceedance moment levels for the quick stop are as much as 1.5 times as large as those for hover. The expected task must be accounted for when defining requirements for installed control moment. Also, the installed total moment for pitch plus roll control must be sufficient to account for simultaneous control usage by the pilot. It cannot be assumed that pilots make independent pitch and roll control inputs.

Finally, it appears that specifying levels for installed control moment by requiring that they equal those levels which the pilot would be expected to exceed 5 percent of the time is not acceptable. However, it may be that acceptable installed control-moment levels would correlate better with those levels exceeded a smaller percent of the time.

2. Height Control

Thrust usage decreased with increased levels of height velocity damping. Lags in the thrust response increased thrust usage; this contrasts with the effect of lags on pitch and roll control-moment usage. With satisfactory levels of Z_w , installed thrust-to-weight ratios of 1.05 were seldom exceeded and $T/W = 1.10$ was never exceeded.

3. Directional Control

Yaw control-moment usage decreased with increased yaw rate damping for the values of yaw rate damping tested, i.e., $|N_r| < 1.0$. Moment usage increased with lags in the yaw response to control inputs, however.

C. Effects of Flight Simulator Motion Cues on Pilot Ratings

For longitudinal and lateral control the addition of flight simulator motion resulted in poorer pilot ratings than those assigned when the same test cases were evaluated without motion. This trend was evident for all cases, regardless of their flying qualities, i.e., whether or not they had been rated satisfactory, unsatisfactory or unacceptable without motion. For both height and yaw control, however, the addition of motion generally resulted in improved ratings for test cases which were rated unsatisfactory or unacceptable without motion. For cases rated satisfactory fixed base, the addition of simulator motion appeared to have little effect on the pilot's rating of height or directional flying qualities.

D. Recommendations for Further Research

It is recommended that the following research be conducted to obtain information pertinent to the further development of MIL-F-83300.

(1) Additional fixed- and moving-base flight simulator studies of control-power usage should be conducted. In these studies, the significance of aircraft, control system and task parameters would be further evaluated and the control-power specification would be tested in more detail.

(2) The ability of rotor-propulsion system stored energy to compensate for limits in installed control power should be investigated in more detail.

(3) Additional unconventional control systems such as on-off (bang-bang) control and velocity-vector (TAGS) control should be evaluated to determine their attributes. Modifications to MIL-F-83300 to extend its coverage to these systems must be explored. Independent thrust-vector control should also be examined in more detail; it appears to be a promising concept, but was only given limited study in this program.

| LEVEL | | 1 | | 2 | | 3 | |
|-------------|--|-----|-----|-----|-----|-----|-----|
| BASIC CONF. | | BC1 | BC2 | BC3 | BC4 | BC5 | BC6 |
| SYMBOL | | ○ | □ | △ | ◇ | ▽ | ◊ |

LEVEL RELATES FLYING QUALITIES TO PITCH AND ROLL DYNAMIC RESPONSE REQUIREMENTS IN
PARAGRAPH 3.2.2 OF MIL-F-83300 (REF. 1)

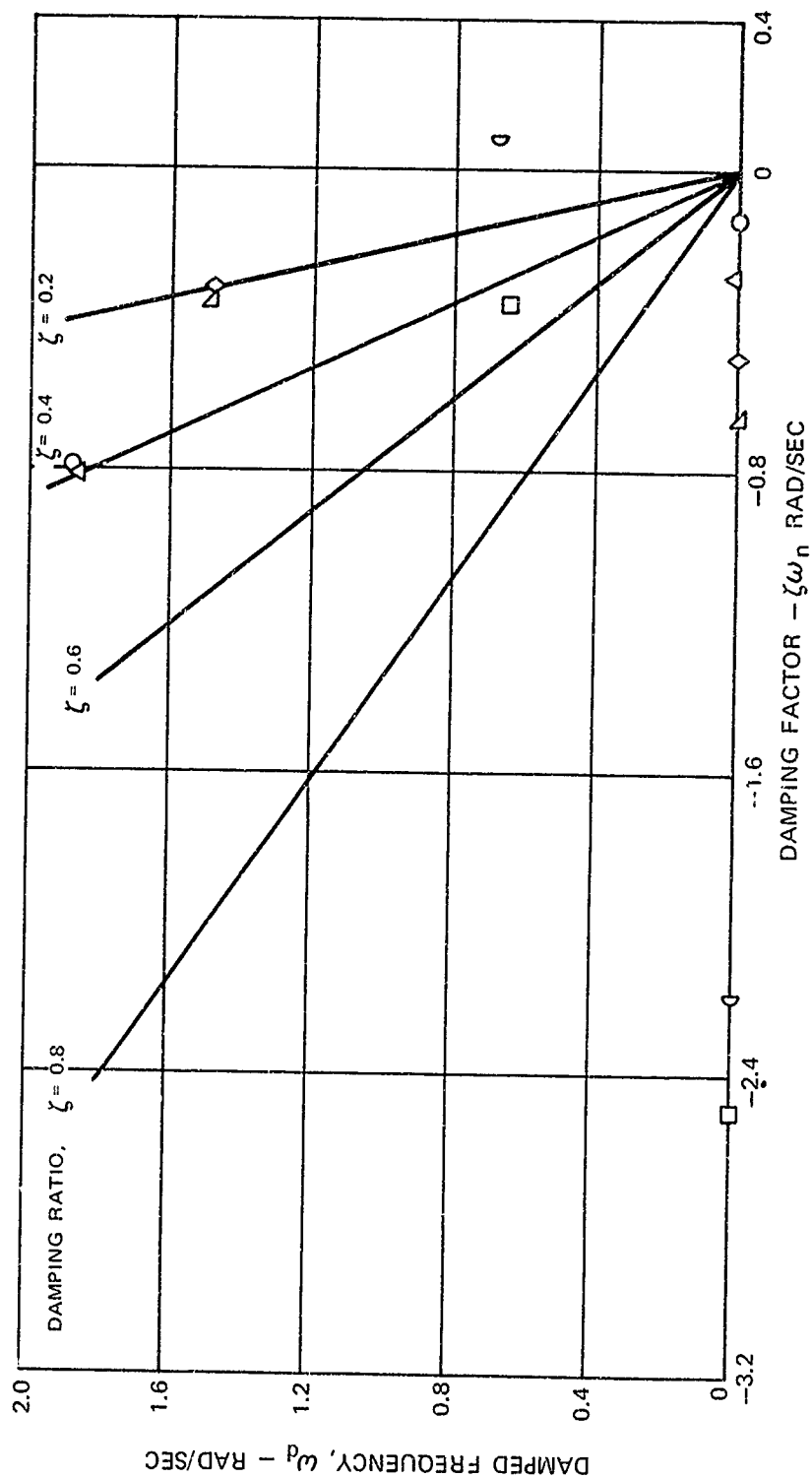


Figure 1. Root Locations for UARL Basic Configurations

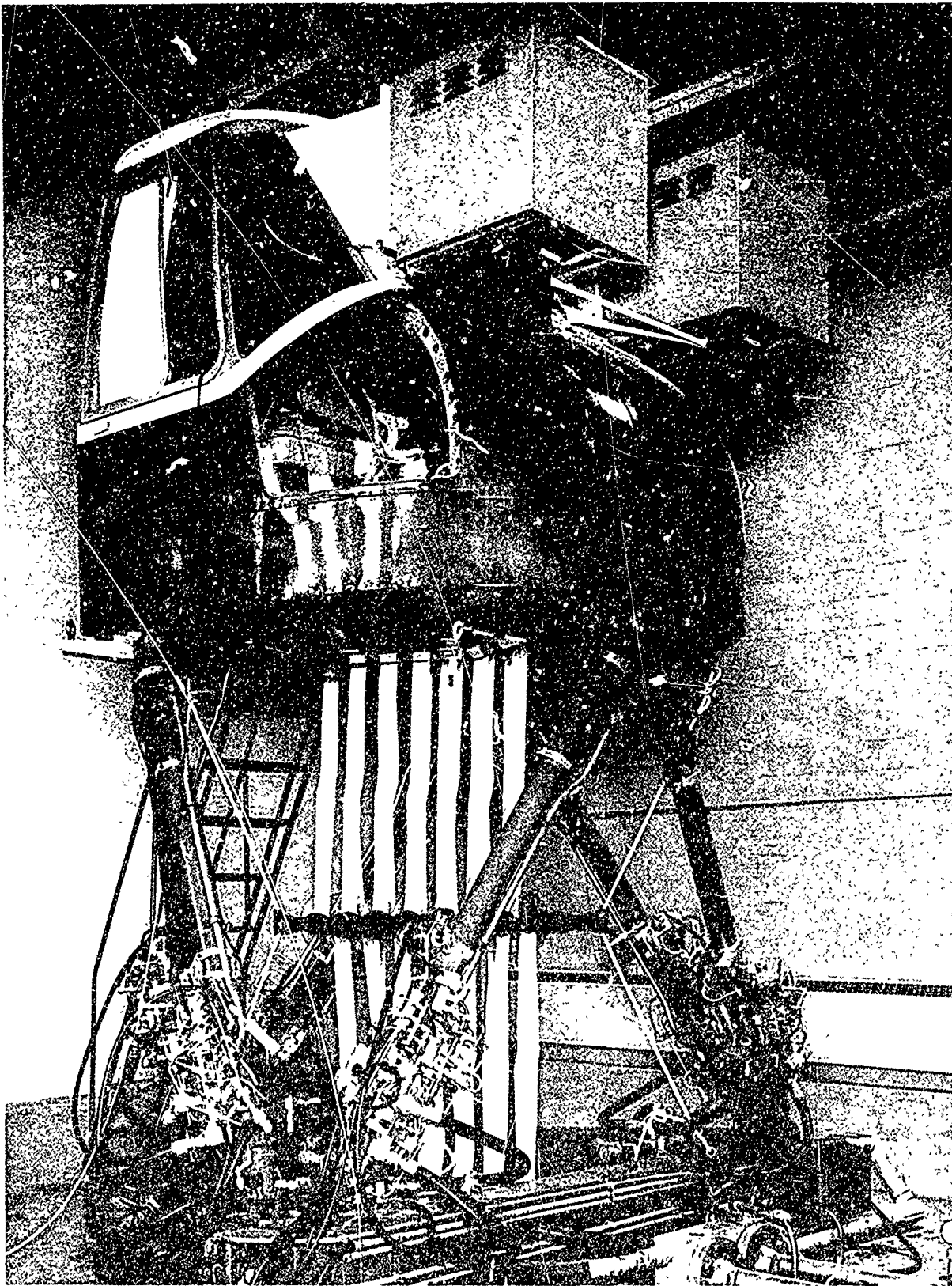


Figure 2. United Aircraft Corporation V/STOL Aircraft Flight Simulator

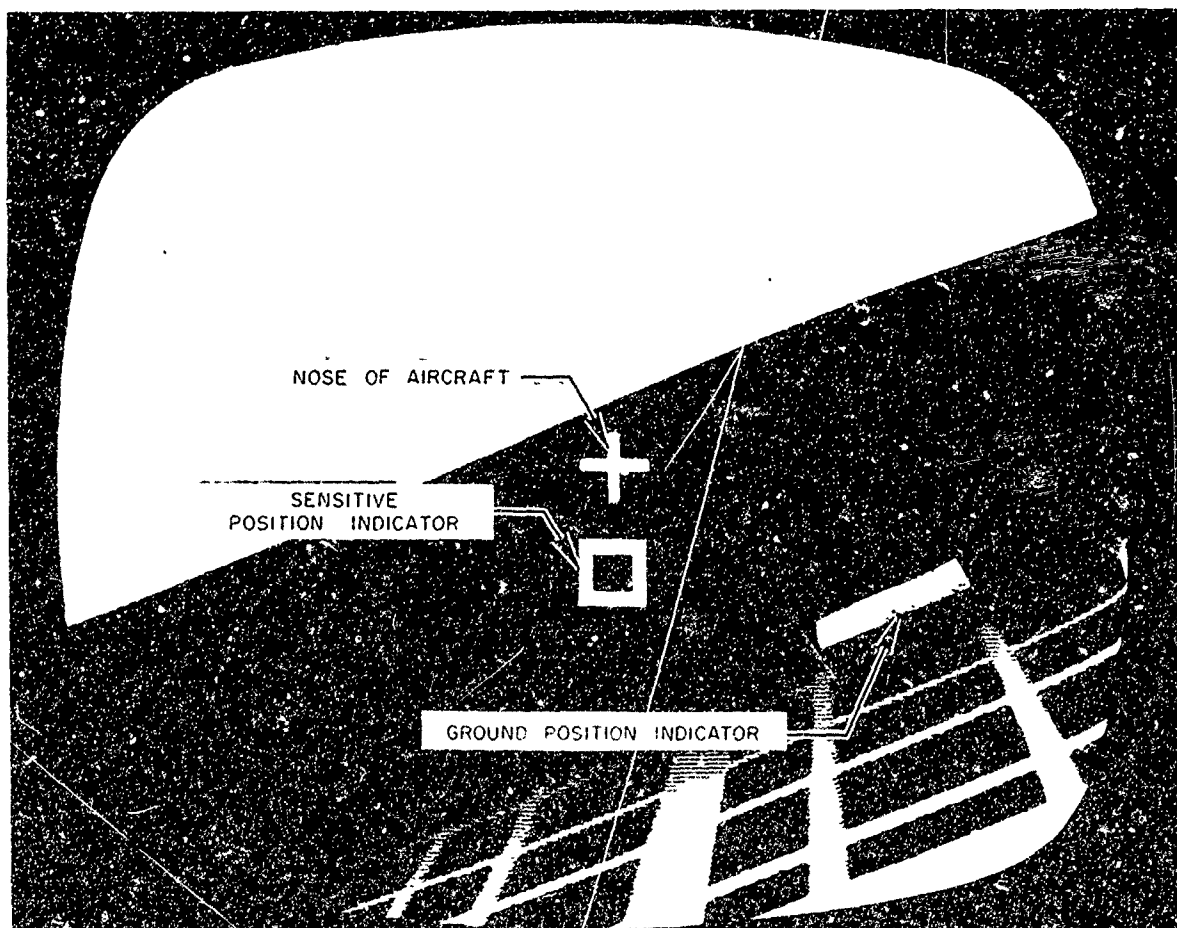


Figure 3. Contact Analog Display for Hovering and Low-Speed Maneuvering Task

| SIMULATION | UARL | | NORAIR |
|----------------|------|----|--------|
| SIMULATOR MODE | FB | MB | MB |
| SYMBOL | ○ | ● | ■ |

$$\sigma_{u_g} = \sigma_{v_g} = 3.4 \text{ FT/SEC}$$

$$U_m = 10 \text{ KTS FROM NORTH}$$

*SEE NOTE ON LEVEL DESIGNATION SHOWN ON FIG. 1

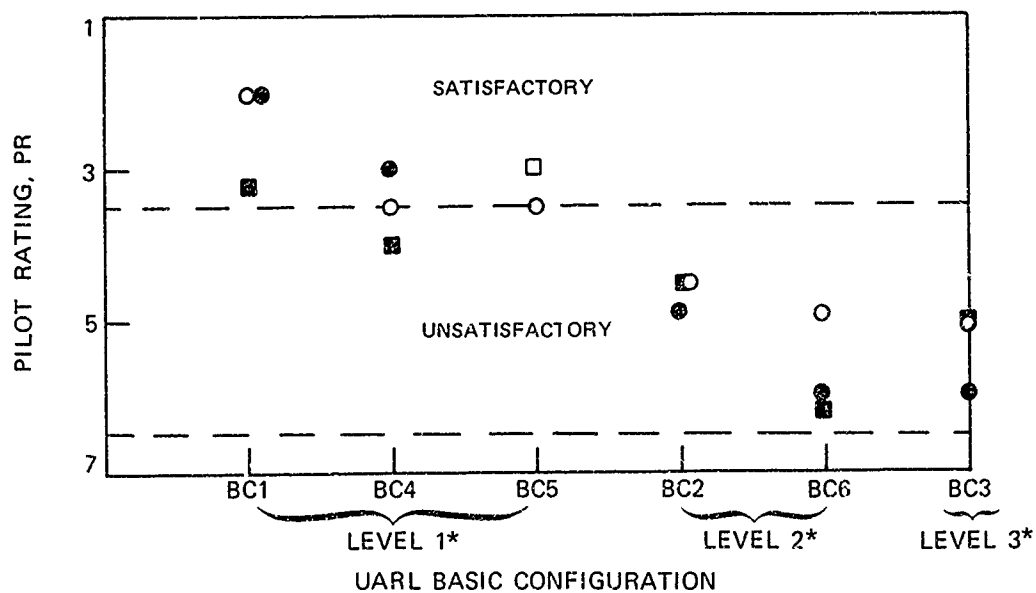


Figure 4. Comparison of Averaged Pilot Ratings from UARL and Norair Simulations for Similar Configurations

| SUBTASK | MAN | OS | TU | HOV |
|---------|-----|----|----|-----|
| SYMBOL | ○ | □ | △ | ◇ |

CONFIGURATION BC1 PILOT B $\sigma_{u_g} = \sigma_{v_g} = 3.4$ FT/SEC

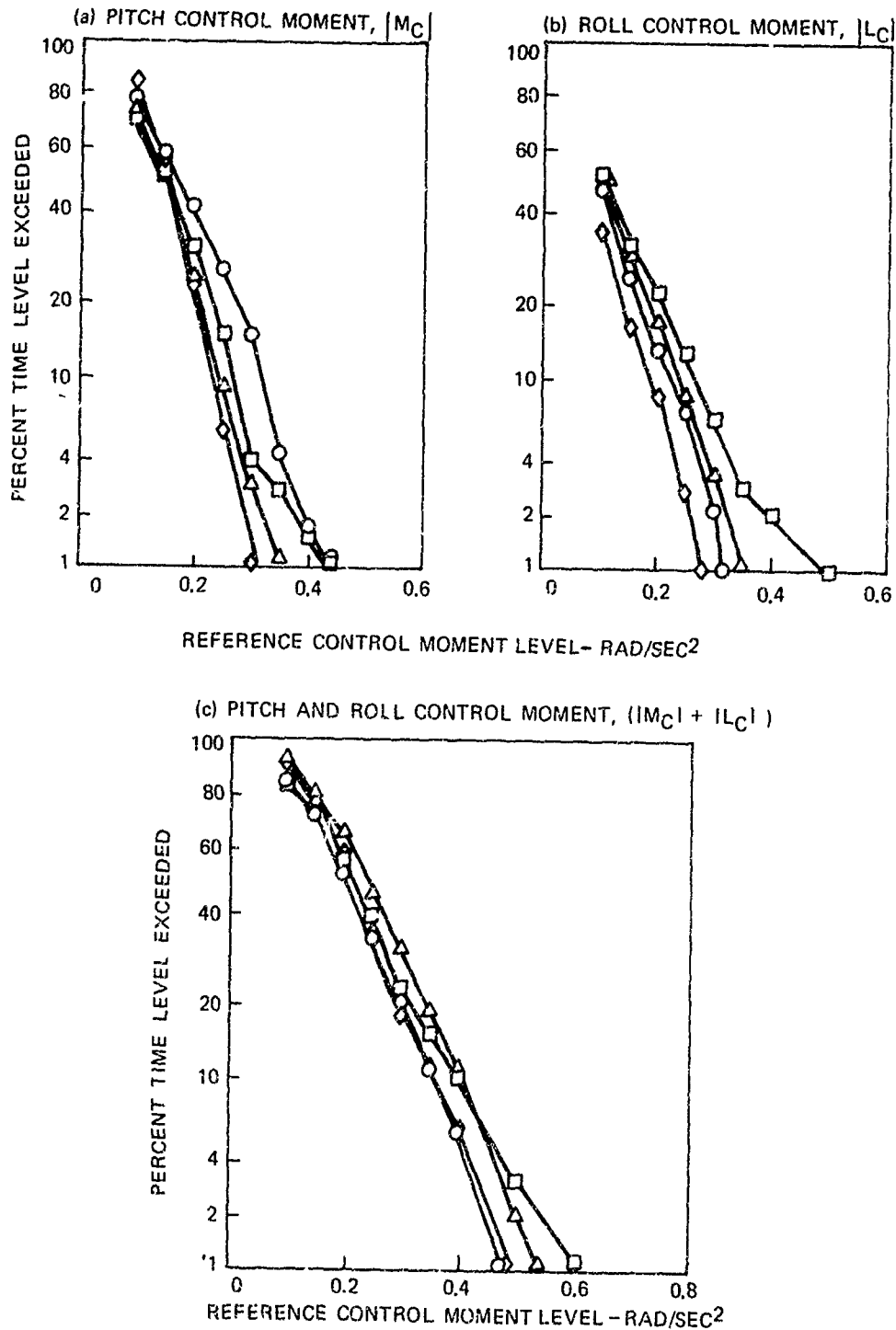


FIGURE 5. Representative Exceedance Plots Showing the Effects of Subtask on Control-Moment Usage

| SIMULATOR MODE, PILOT | FIXED, A | | FIXED, B | |
|--------------------------|----------|-----|----------|-----|
| | BC4 | BC1 | BC4 | BC1 |
| SYMBOL | O | ● | □ | ▲ |

BC1, BC4 LEVEL 1 CONFIGURATIONS $\sigma_{u_g} = \sigma_{v_g} = 3.4 \text{ FT/SEC}$

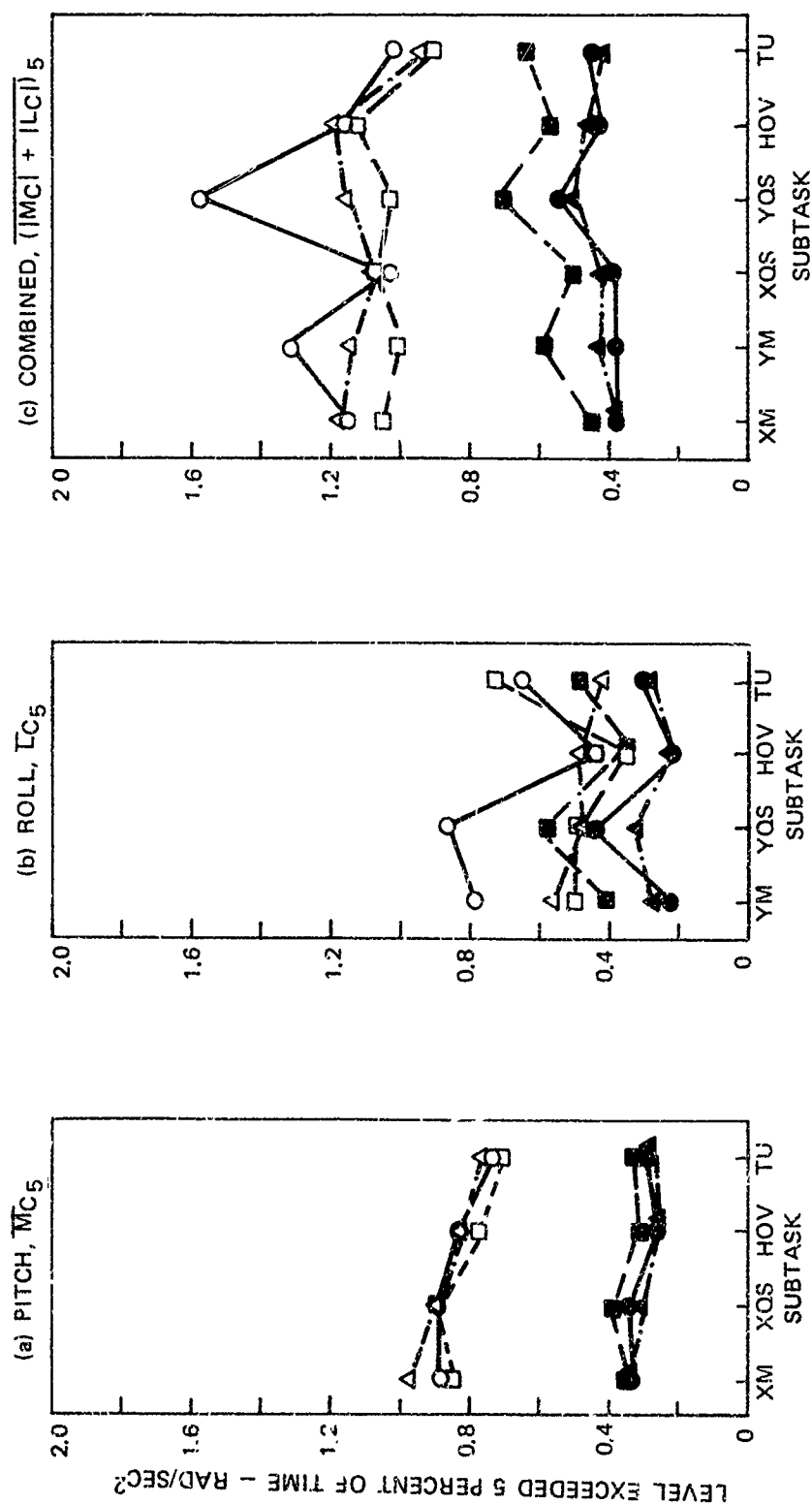
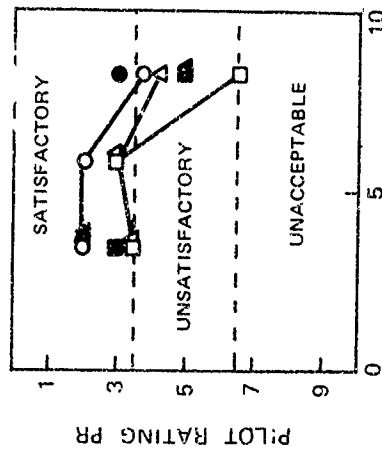


FIGURE 6. Variations in Moment Level Exceeded Five Percent of Time for Two Pilots and Fixed- and Moving-Base Simulator Operation

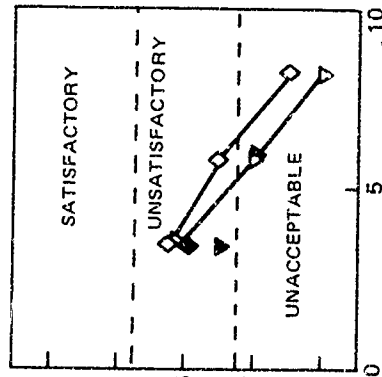
| LEVEL * | 1 | | | | | | | | | | 2 | | | 3 | | | |
|----------------|-----|----|---|-----|----|---|-----|----|---|-----|----|---|-----|----|-----|----|----|
| BASIC CONF. | BC1 | | | BC4 | | | BC5 | | | BC2 | | | BC6 | | BC3 | | |
| SIMULATOR MODE | FB | MB | | FB | MB | | FB | MB | | FB | MB | | FB | MB | | FB | MB |
| SYMBOL | ○ | ● | □ | □ | ■ | △ | △ | ▲ | ◆ | ◇ | ▽ | ▼ | ▲ | ▲ | ▲ | ▲ | ▲ |

* LEVEL APPLIES TO BASIC CONFIGURATIONS ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES

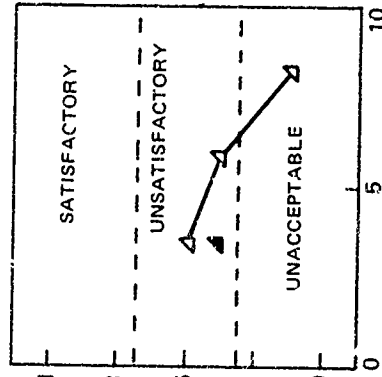
(a) LEVEL 1 CONFIGURATIONS*



(b) LEVEL 2 CONFIGURATIONS*



(c) LEVEL 3 CONFIGURATIONS*



RMS TURBULENCE INTENSITY, $\sigma_{u_g} = \sigma_{v_g} - \text{FT/SEC}^2$

Figure 7. Variation in Pilot Rating with Turbulence Intensity

| TURBULENCE INTENSITY INTERVAL | 3.4-5.8 | | 5.8-8.2 | | 8.2-11.2 | |
|-------------------------------|---------|----|---------|----|----------|----|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ |

* LEVEL APPLIED TO BASIC CONFIGURATIONS ONLY DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

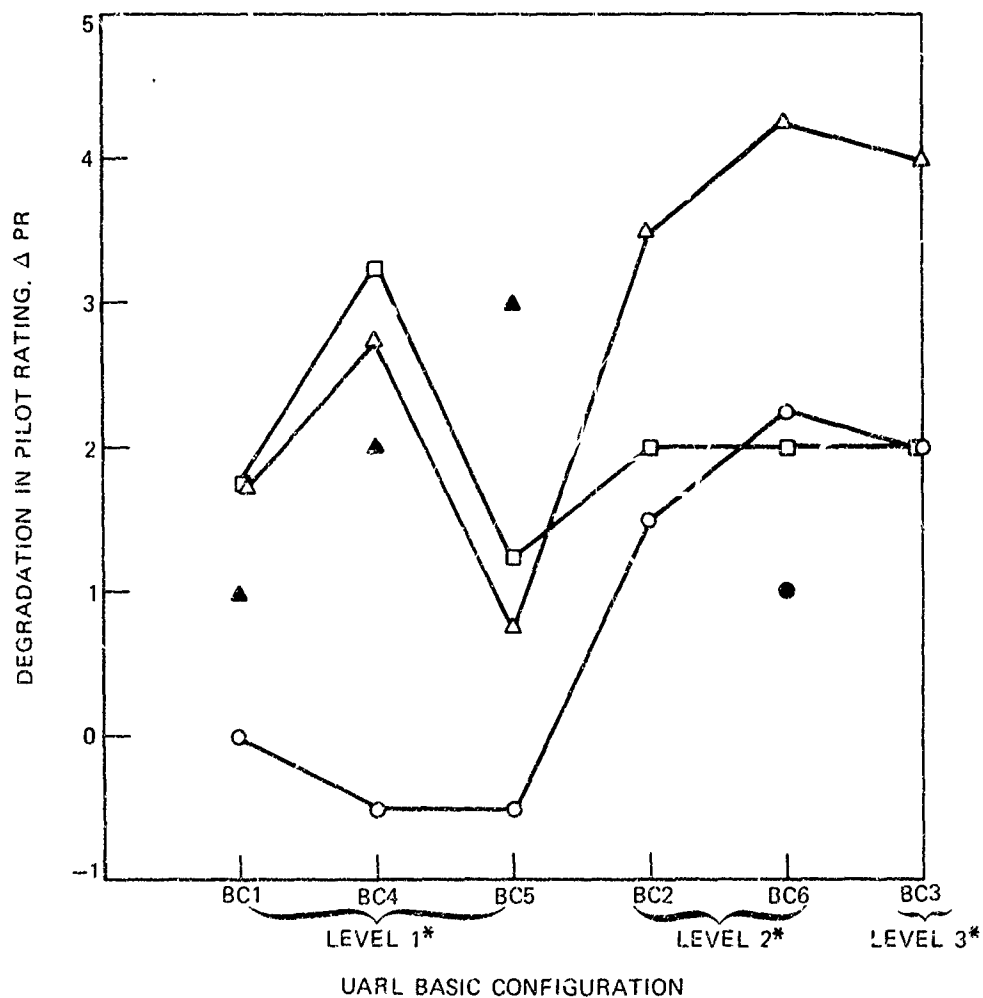


Figure 8. Effect of Pitch and Roll Dynamics Level on Degradation in Pilot Rating with Turbulence Intensity

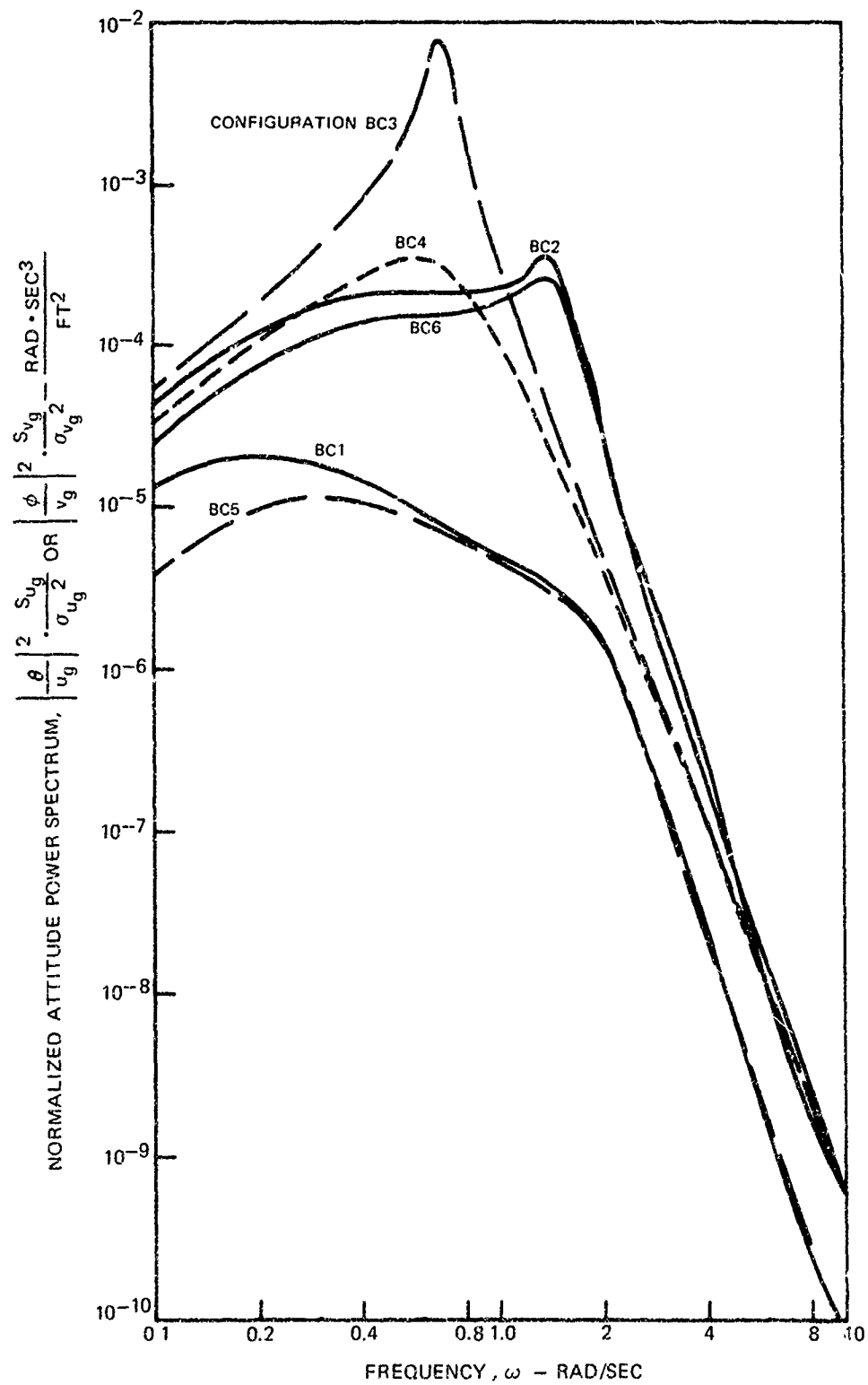


Figure 9. Power Spectrum of Open-Loop Attitude Response to Simulated Turbulence for Basic Configurations

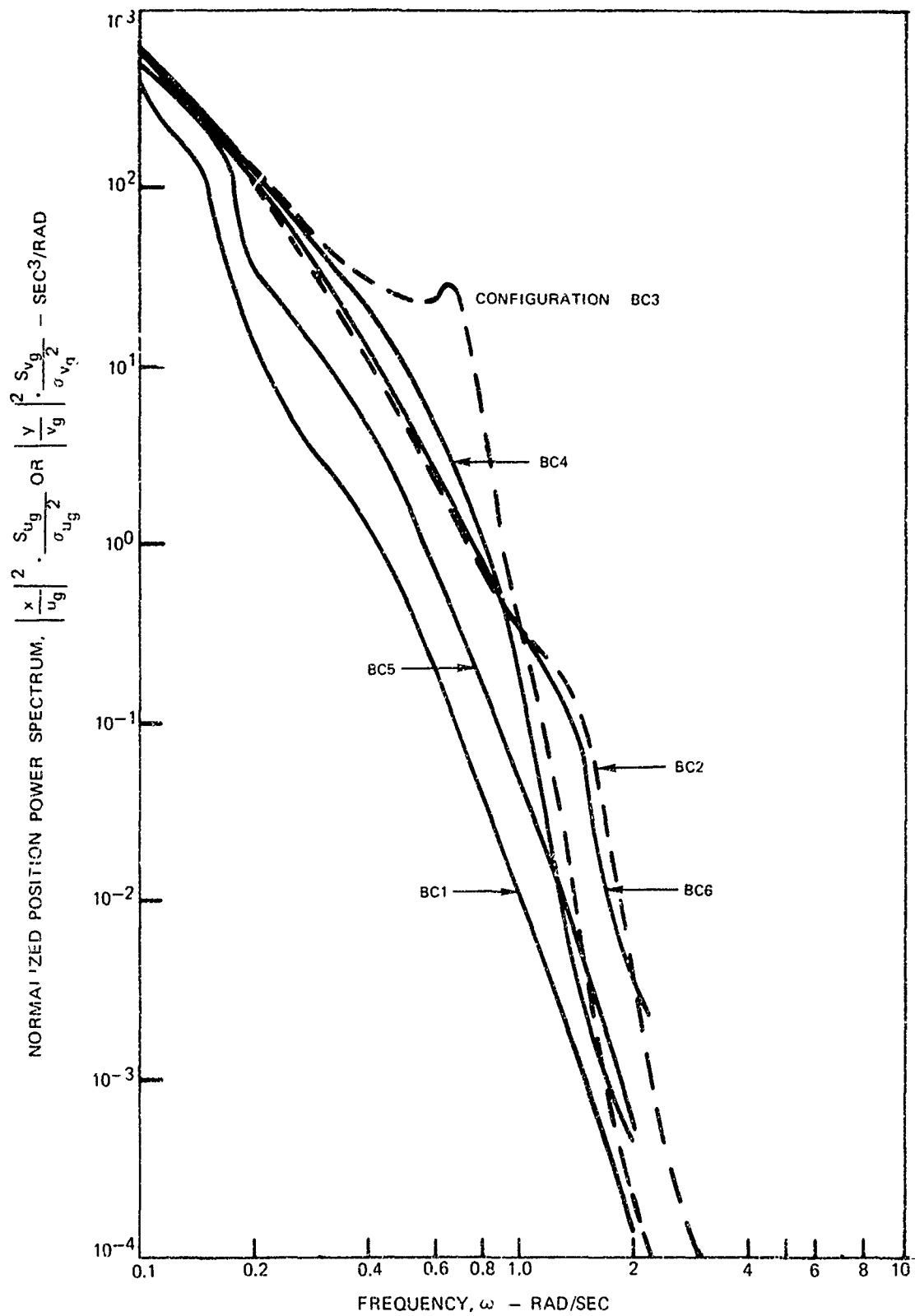


Figure 10. Power Spectrum of Open-Loop Position Response to Simulated Turbulence for Basic Configurations

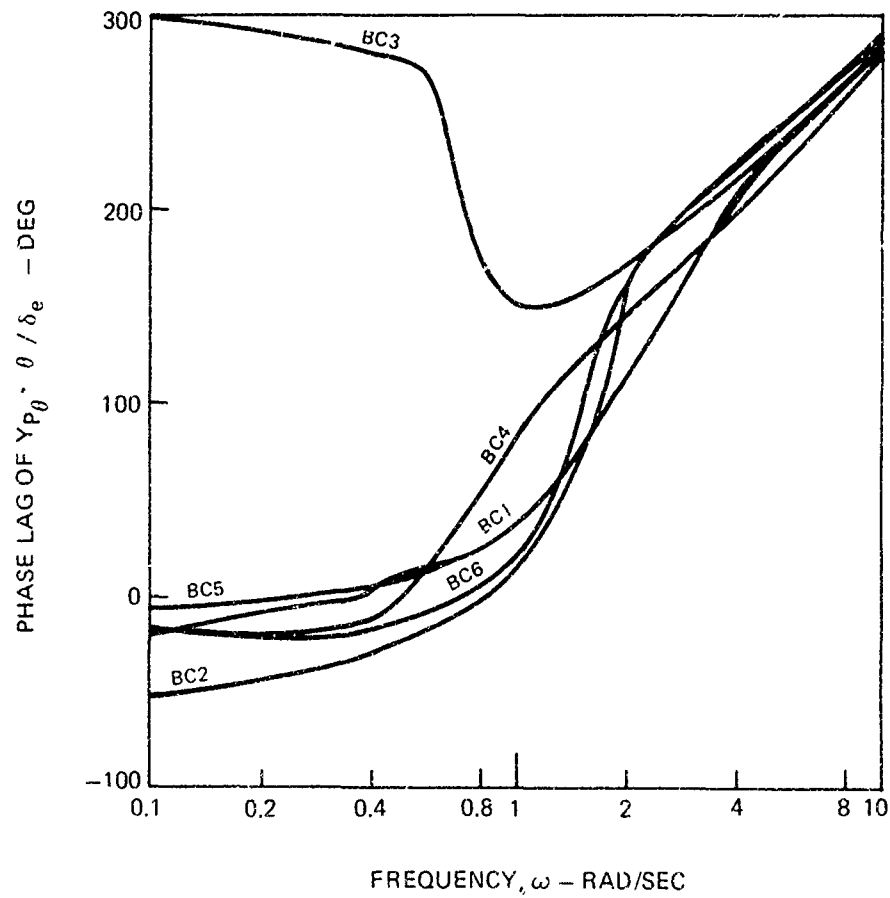


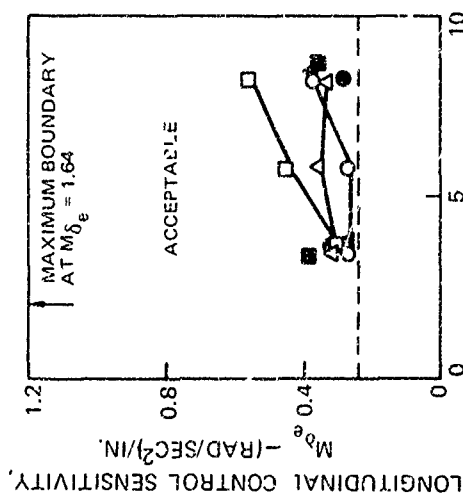
Figure 11. Phase Lag of Pilot-Pitch (Roll) Open-Loop Dynamics for UARL Basic Configurations

| LEVEL* | | 1 | | | | 2 | | | | 3 | |
|----------------|--|-----|----|-----|----|-----|----|-----|----|-----|----|
| BASIC CONF. | | BC1 | | BC4 | | BC5 | | BC2 | | BC3 | |
| SIMULATOR MODE | | FB | MB | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL | | ○ | ● | □ | ■ | △ | ▲ | ◇ | ◆ | ▽ | ▼ |

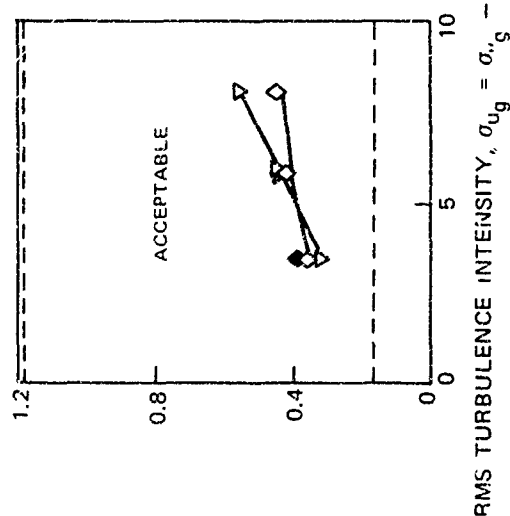
* LEVEL APPLIES TO BASIC CONFIGURATIONS ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

DASHED LINES SHOW MIL-F-83300 BOUNDARIES FOR ACCEPTABLE M_{δ_e} BOUNDARIES BASED ON SPECIFIED MINIMUM AND MAXIMUM ATTITUDE RESPONSE (NORMALIZED WITH CONTROL COMMAND MAGNITUDE) ONE SECOND AFTER CONTROL INPUT

(a) LEVEL 1 CONFIGURATIONS*



(b) LEVEL 2 CONFIGURATIONS*



(c) LEVEL 3 CONFIGURATION *

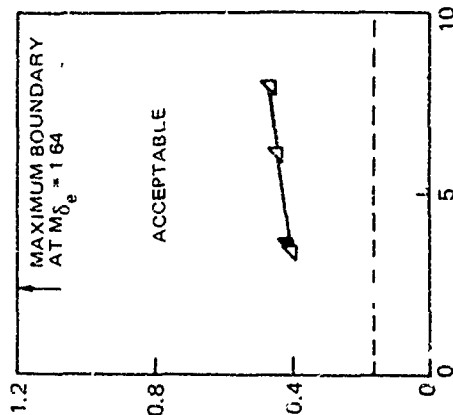


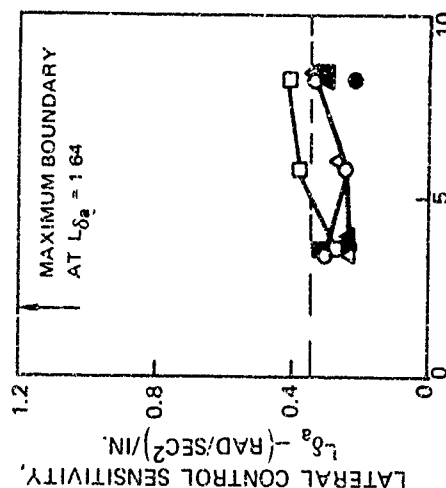
Figure 12. Longitudinal Control Sensitivities from Turbulence Study

| LEVEL # | 1 | | | | | | | | | | 2 | | | | 3 | |
|----------------|-----|----|---|-----|----|---|-----|----|---|-----|----|---|-----|----|---|-----|
| | BC1 | | | BC4 | | | BC5 | | | BC2 | | | BC6 | | | BC3 |
| | FB | MB | ○ | FB | MB | □ | FB | MB | △ | FB | MB | ◇ | FB | MB | ▽ | |
| SIMULATOR MODE | | | | | | | | | | | | | | | | |
| SYMBOL | | | | | | | | | | | | | | | | |

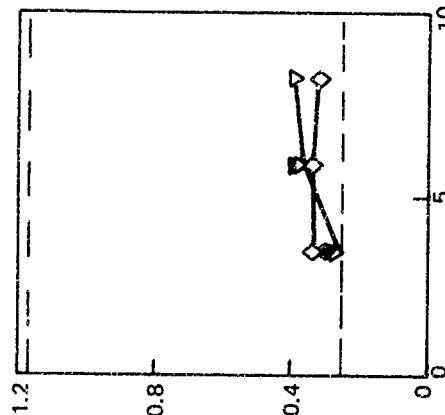
* LEVEL APPLIES TO BASIC CONFIGURATIONS ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

DASHED LINES SHOW MIL-F-83300 BOUNDARIES FOR ACCEPTABLE $L_{\delta a}$. SEE NOTE ON FIG. 12.

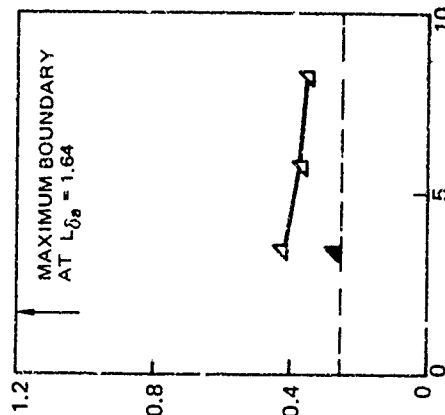
(a) LEVEL 1 CONFIGURATIONS*



(b) LEVEL 2 CONFIGURATIONS*



(c) LEVEL 3 CONFIGURATION*



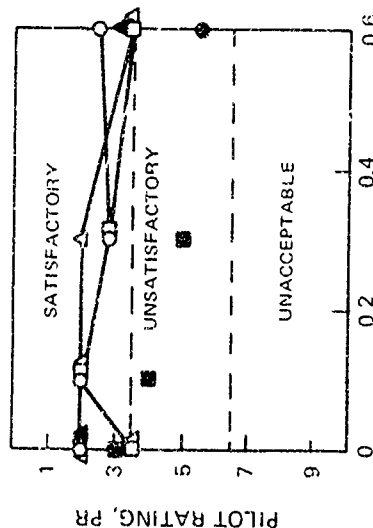
RMS TURBULENCE INTENSITY, σ_{ug} = FT/SEC

Figure 13. Lateral Control Sensitivities from Turbulence Study

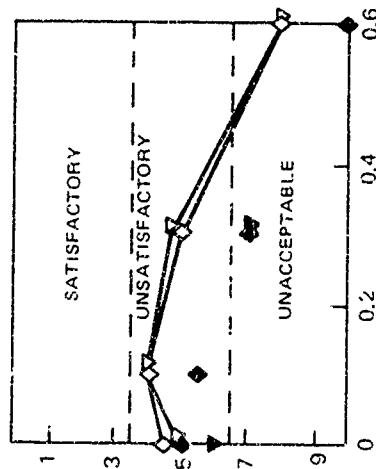
| LEVEL * | | 1 | | | 2 | | | 3 | | |
|----------------|--|-----|--|--|-----|--|--|-----|--|--|
| BASIC CONF | | BC1 | | | BC2 | | | BC3 | | |
| SIMULATOR MODE | | FB | | | FB | | | FB | | |
| SYMBOL | | C | | | C | | | C | | |

* LEVEL APPLIES TO BASIC CONFIGURATIONS ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

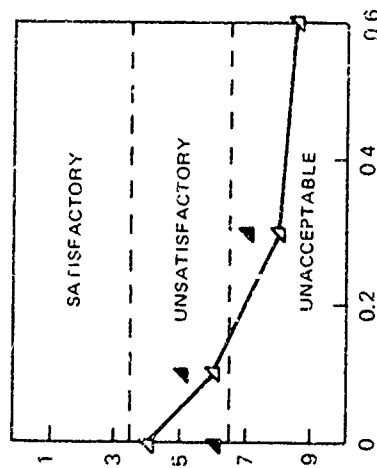
(a) LEVEL 1 CONFIGURATIONS*



(b) LEVEL 2 CONFIGURATIONS*



(c) LEVEL 3 CONFIGURATIONS*



FIRST-ORDER LAG TIME CONSTANT, $\tau_e = \tau_a$, SFC

Figure 14. Variation in Pilot Rating with Time Constant of First-Order Lag in Control Response

| LAG TIME CONSTANT INTERVAL | 0-0.3 | | 0.3-0.6 | | 0-0.6 | |
|----------------------------|-------|----|---------|----|-------|----|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ |

* LEVEL APPLIES TO BASIC CONFIGURATIONS ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

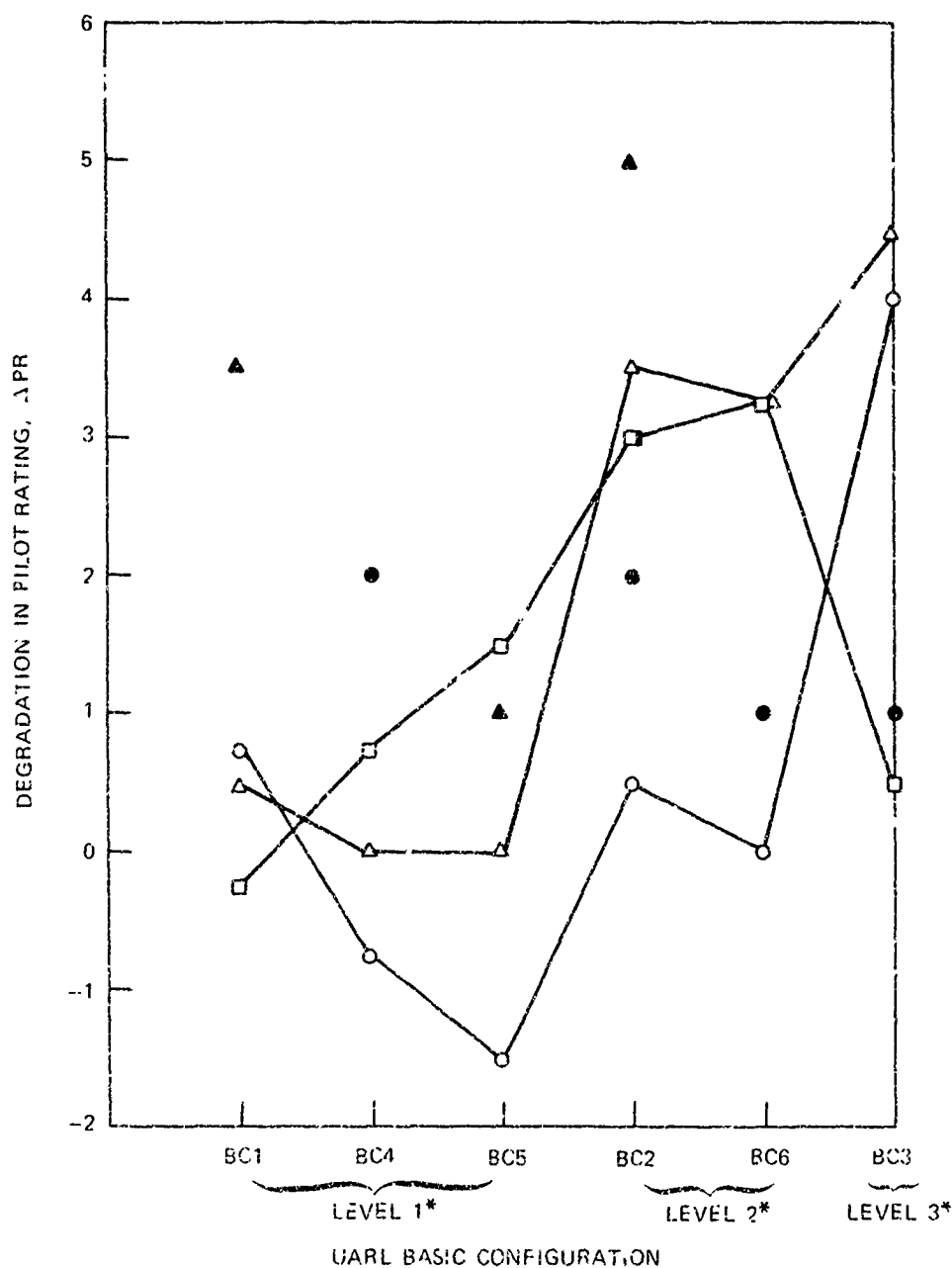


Figure 15. Effect of Pitch and Roll Dynamics Level on Degradation in Pilot Rating with First-Order Lag Time Constant

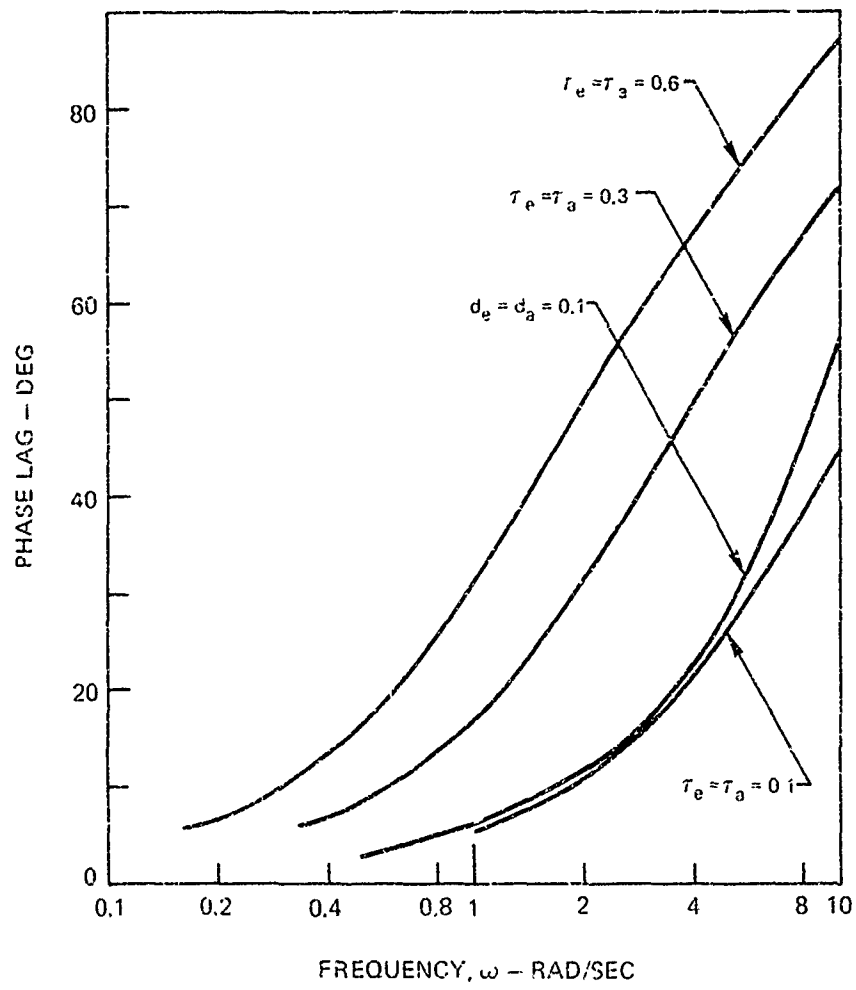


Figure 16. Phase Lags from First-Order Lags and Delays

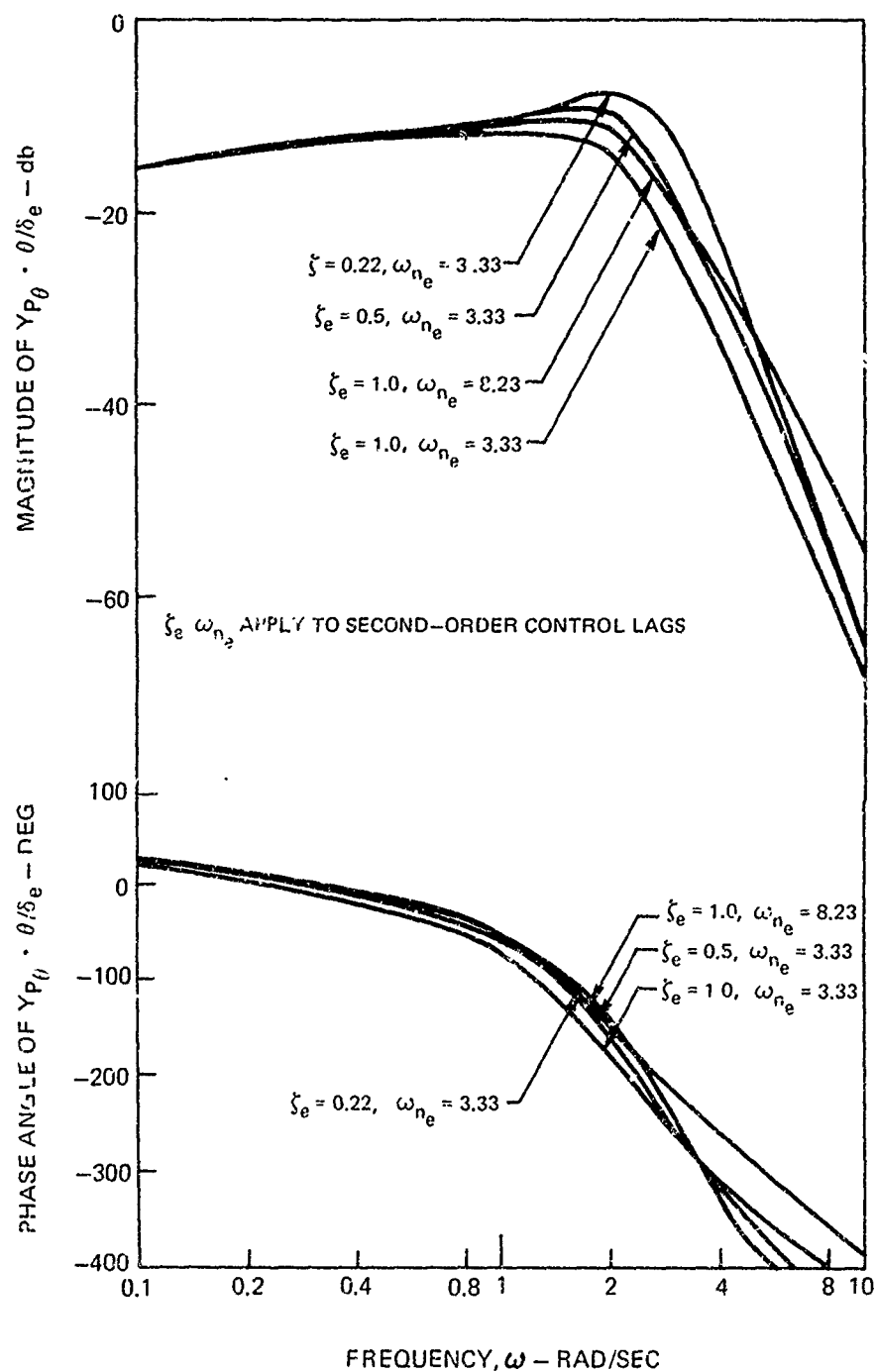


Figure 17. Magnitude and Phase Characteristics for Pilot-Pitch (Roll) Open-Loop Dynamics with Second-Order Control Lags

○ PILOT B, FIXED BASE, CONF. 8C1

NATURAL FREQUENCY OF SECOND-ORDER LAG,
 $\omega_{n_e} = \omega_{n_a} = 3.33$ EXCEPT WHERE INDICATED

IDENTICAL LAGS PRESENT IN BOTH PITCH AND ROLL
CONTROL RESPONSE

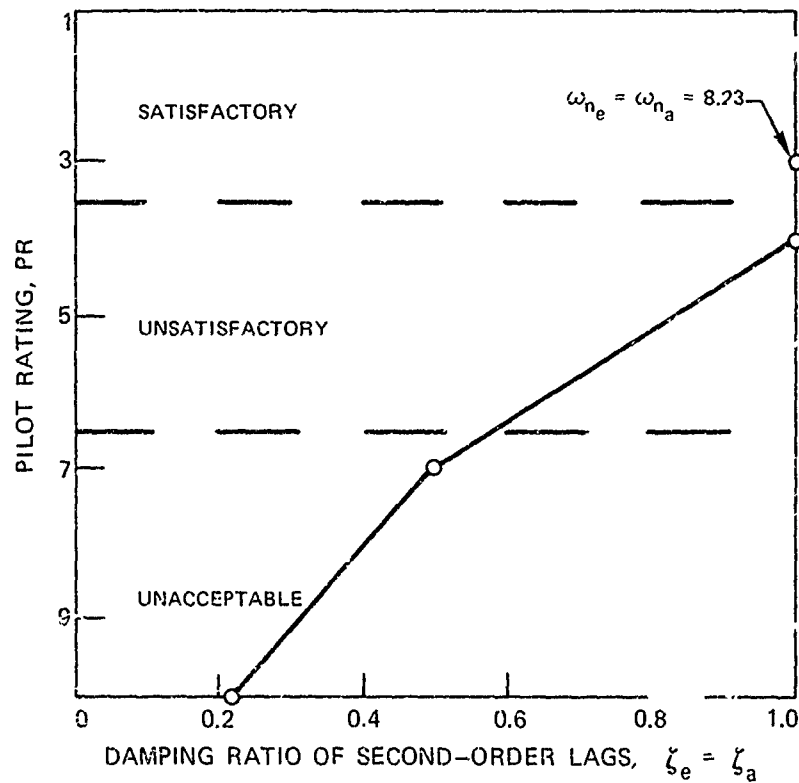
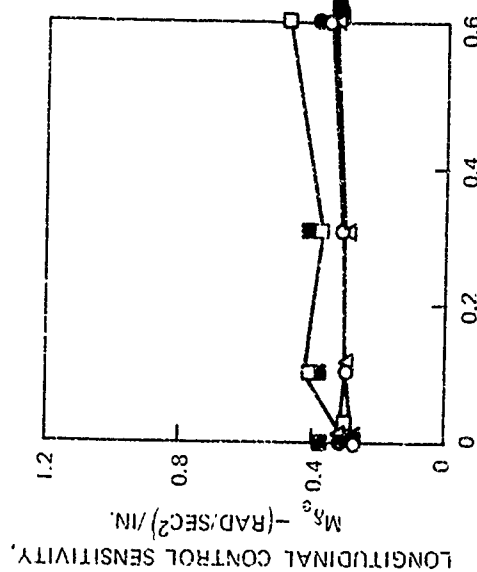


Figure 18. Pilot Ratings for Second-Order Lags in Pitch and Roll Control Response

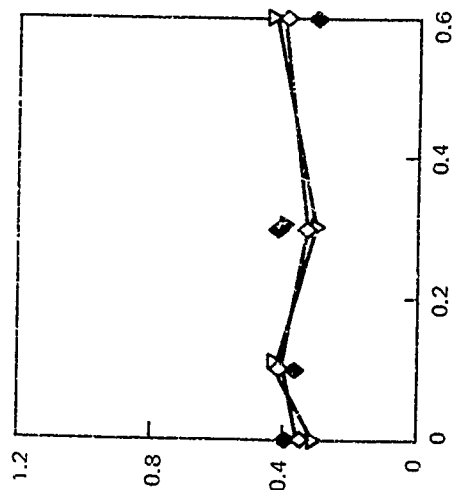
| LEVEL * | | | | | | | | | |
|----------------|--|-----|----|-----|-----|----|-----|----|-----|
| 1 | | | | | 2 | | | | |
| BASIC CONF. | | BC1 | | 1C4 | BC5 | | BC2 | | BC3 |
| SIMULATOR MODE | | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL | | ○ | ● | □ | ■ | △ | ▲ | ◇ | ▼ |

* LEVEL APPLIES TO BASIC CONFIGURATION ONLY DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN
GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

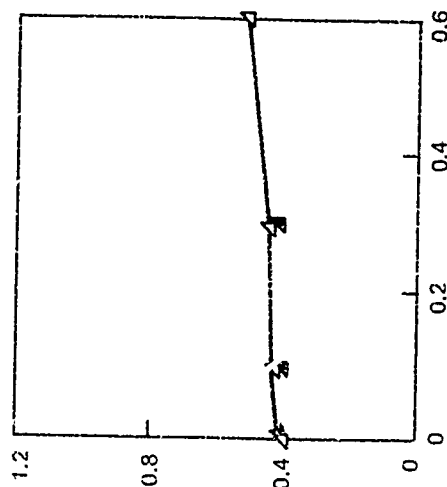
(a) LEVEL 1 CONFIGURATIONS *



(b) LEVEL 2 CONFIGURATIONS *



(c) LEVEL 3 CONFIGURATIONS *



FIRST-ORDER LAG TIME CONSTANT, $\tau_e = \tau_a - \text{SEC}$

Figure 19. Longitudinal Control Sensitivity Results Showing the Effects of First-Order Control Lag

| LEVEL # | 1 | | | | | | 2 | | | | | | 3 | |
|---------|-----|---|----|-----|---|----|-----|---|----|-----|---|----|-----|---|
| | BC1 | | | BC4 | | | BC5 | | | BC2 | | | BC3 | |
| | FB | | MB | FB | | MB | FB | | MB | FB | | MB | FB | |
| | ○ | ● | □ | ■ | △ | ▲ | ◇ | ◆ | ▽ | ▼ | △ | ▲ | ◇ | ◆ |

* LEVEL APPLIES TO BASIC CONFIGURATIONS ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

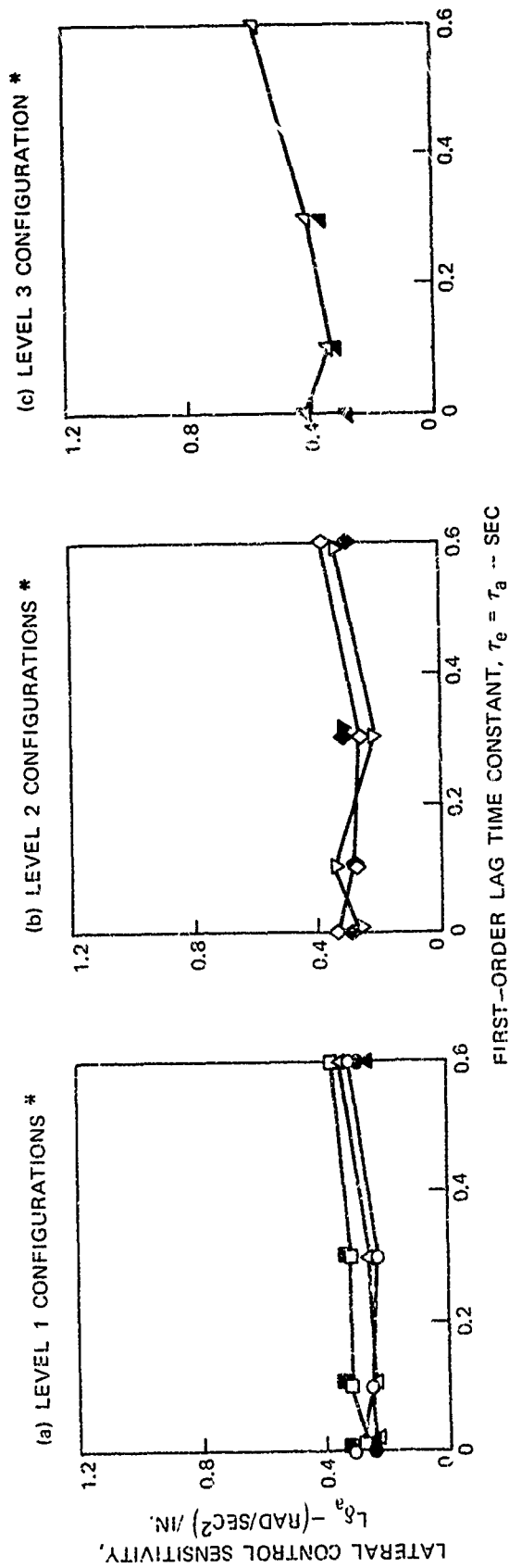


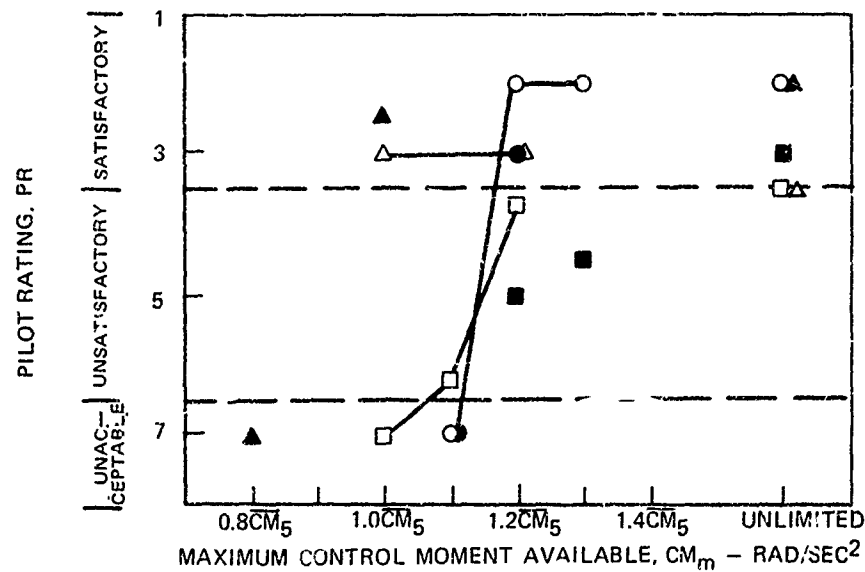
Figure 20. Lateral Control Sensitivity Results Showing the Effects of First-Order Control Lag

| BASIC CONF. | BC1 | | BC4 | | BC5 | | BC6 | |
|----------------|-----|----|-----|----|-----|----|-----|----|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ | ◇ | ◆ |

FIVE PERCENT EXCEEDANCE LEVELS, \bar{C}_5 FOR PITCH, ROLL, AND YAW, RESPECTIVELY, WERE:

| BASIC CONF. | BC1 | BC4 | BC5 | BC6 |
|------------------------|-------|-------|-------|-------|
| PITCH, \bar{M}_{C_5} | 0.330 | 0.820 | 0.380 | 0.890 |
| ROLL, \bar{L}_{C_5} | 0.380 | 0.605 | 0.360 | 0.750 |
| YAW, \bar{N}_{C_5} | 0.110 | 0.175 | 0.150 | 0.170 |

(a) LEVEL 1 CONFIGURATIONS FOR UNLIMITED CONTROL MOMENTS



(b) LEVEL 2 CONFIGURATION FOR UNLIMITED CONTROL MOMENTS

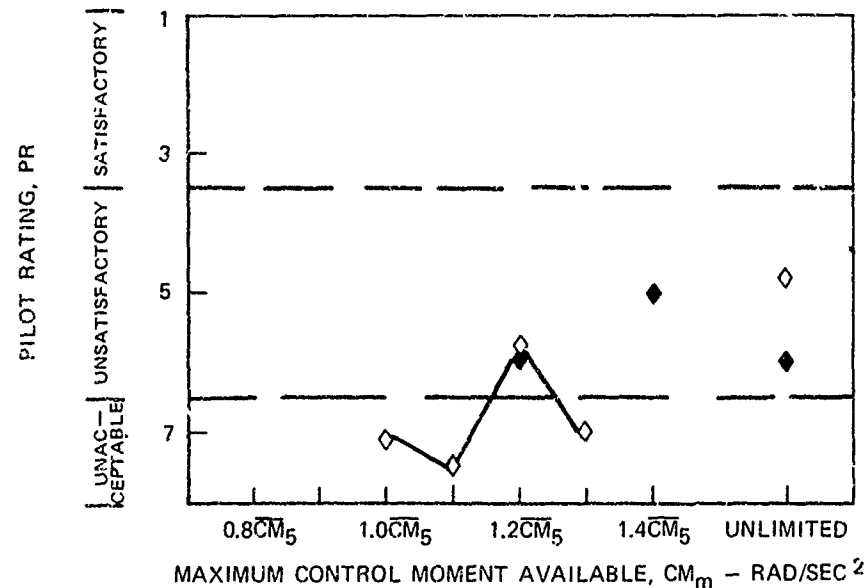


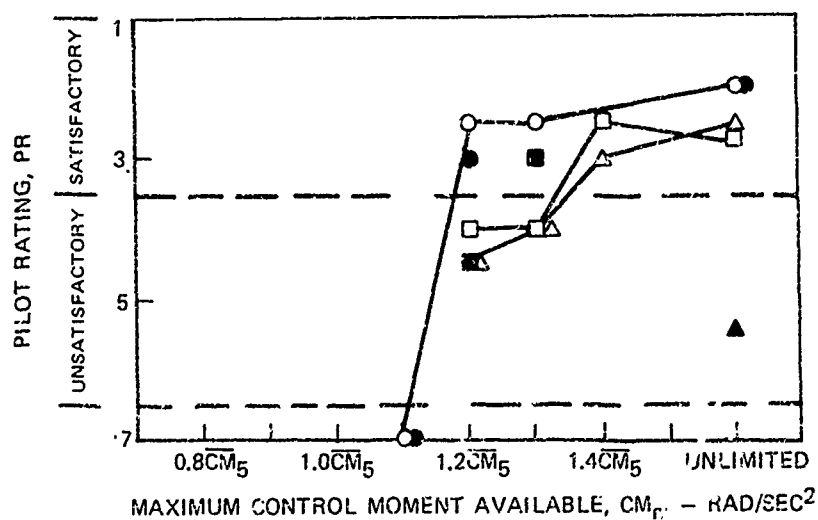
Figure 21. Pilot Rating Results for Control Moment Limits

| LAG TIME CONSTANT | $\tau_e = \tau_a = 0$ | | $\tau_e = \tau_a = 0.5$ | | $\tau_e = \tau_a = 0.6$ | |
|-------------------|-----------------------|----|-------------------------|----|-------------------------|----|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ |

0.1 SEC DELAY IN CONTROL RESPONSE FOR ALL TEST CASES

\overline{CM}_5 : AVERAGED 5 PERCENT EXCEEDANCE MOMENT LEVELS FOR PITCH, ROLL, YAW

(a) BC1 $\overline{CM}_5 = 0.330, 0.380, 0.110$ RAD/SEC² FOR PITCH, ROLL, YAW, RESPECTIVELY



(b) BC5 $\overline{CM}_5 = 0.380, 0.360, 0.150$ RAD/SEC² FOR PITCH, ROLL, YAW, RESPECTIVELY

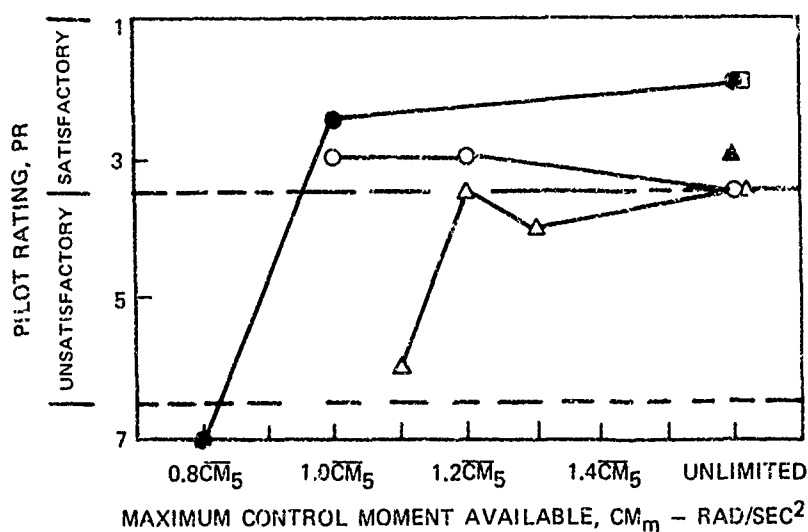


Figure 22. Pilot Ratings Showing the Effects of Control Moment Limits with First-Order Control System Lags

| BASIC CONF. | BC1 | | BC4 | | BC5 | | BC6 | |
|-------------|-----|----|-----|----|-----|----|-----|----|
| | FB | MB | FB | MB | FB | MB | FB | MB |
| Str.: MODE | | | | | | | | |
| S / MB, L | ○ | ● | □ | ■ | △ | ▲ | ◇ | ◆ |

ΔM_c : MAXIMUM PITCH CONTROL MOMENT AVAILABLE THROUGH STORED ENERGY.
EQUAL TO 30 PERCENT OF INSTALLED CONTROL MOMENT, M_{cm} , UNLESS NOTED OTHERWISE.

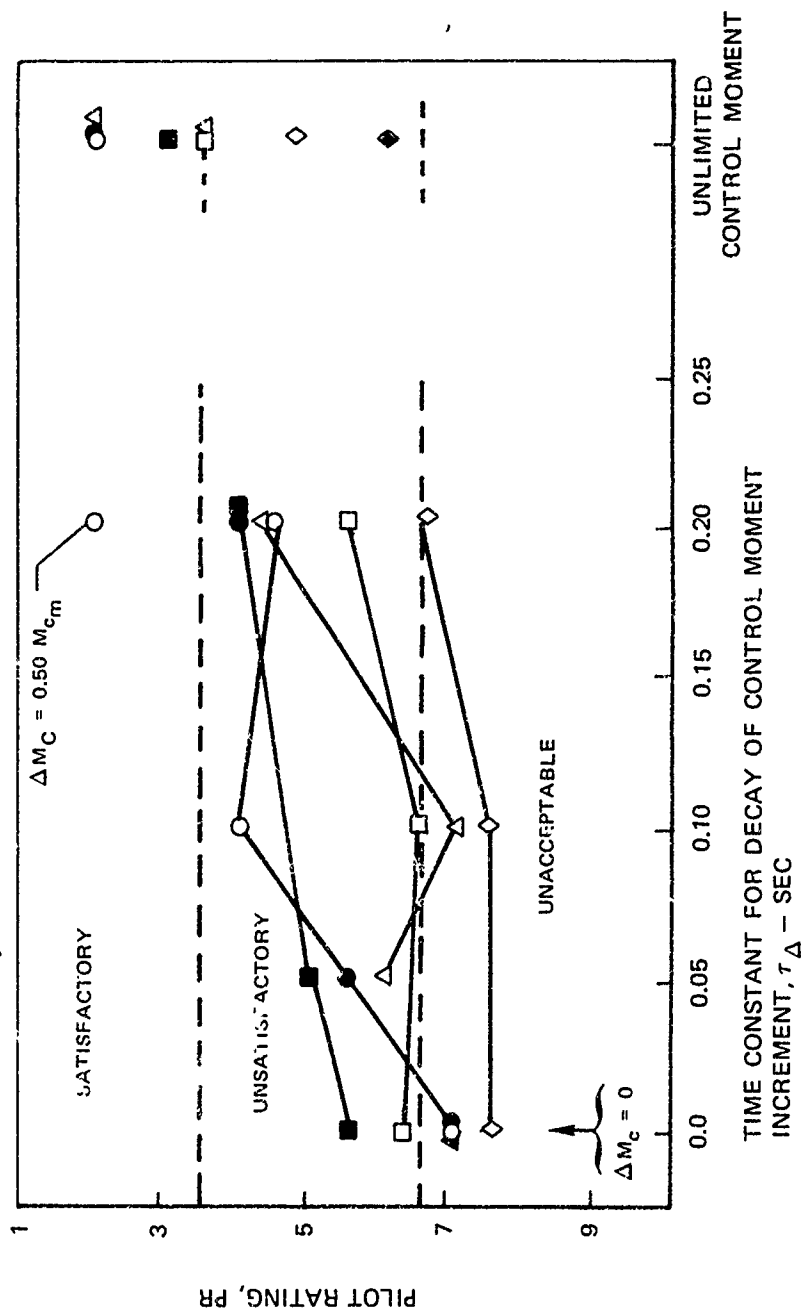


Figure 23. Change in Pilot Rating with Level of Incremental Pitch Control-Moment Available Through Stored Energy

BASIC CONFIGURATION BC1 PILOT B MANUEVERING SUBTASK

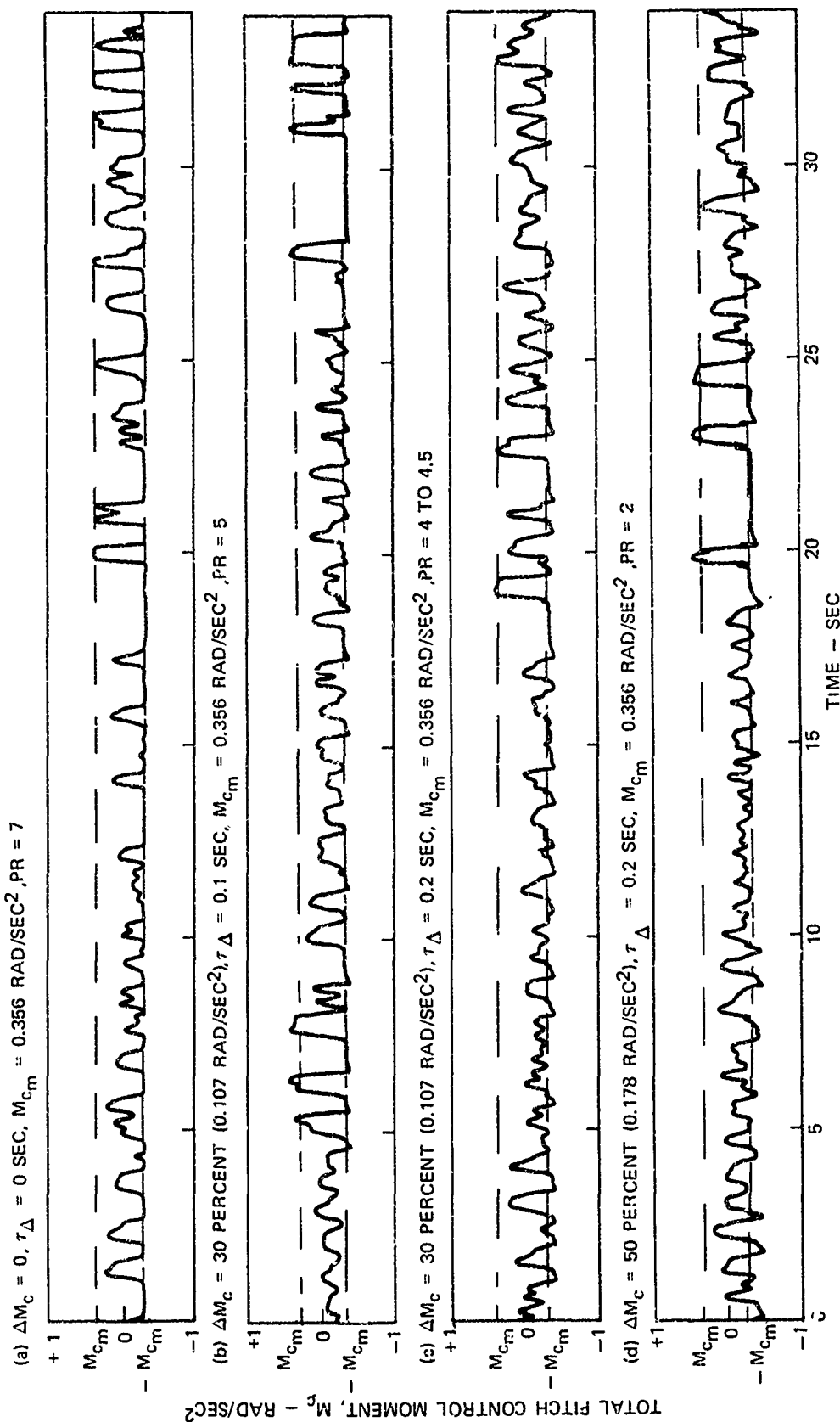


Figure 24. Time Histories of Pitch Control-Moment Usage for the Maneuvering Task with Incremental Moment Available Through Stored Energy

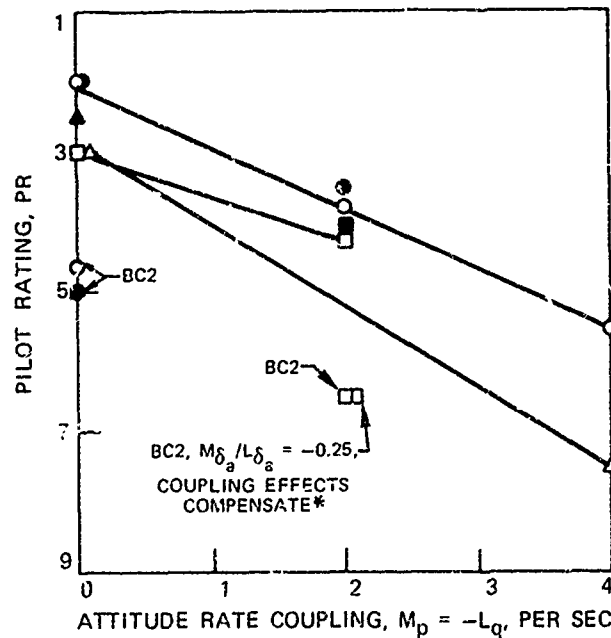
| | | | | | | |
|--|----|----|------|----|------|----|
| $M_{\delta_a}/L_{\delta_a} = -L_{\delta_e}/M_{\delta_e}$ | 0 | | 0.25 | | 0.50 | |
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ |

CONFIGURATION BC1 EXCEPT WHERE OTHERWISE INDICATED

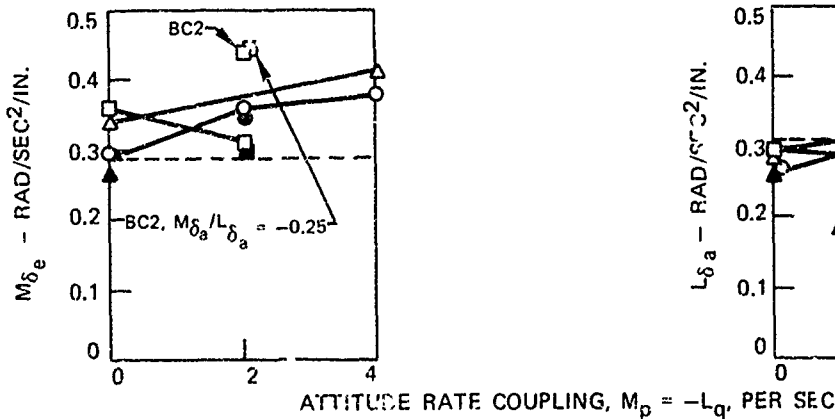
* CONTROL AND RATE COUPLING EFFECTS ADDITIVE, I.E., CONTROL INPUTS CAUSE ATTITUDE RATES WHICH INDUCE COUPLING MOTION IN SAME DIRECTION AS CONTROL COUPLING, UNLESS OTHERWISE NOTED

DASHED LINES INDICATE MIL-F-83300 MINIMUM SENSIVITY BOUNDARY, SEE NOTE ON FIG. 12.

(a) PILOT RATING



(b) LONGITUDINAL CONTROL SENSITIVITIES, M_{δ_e}



(c) LATERAL CONTROL SENSITIVITIES, L_{δ_a}

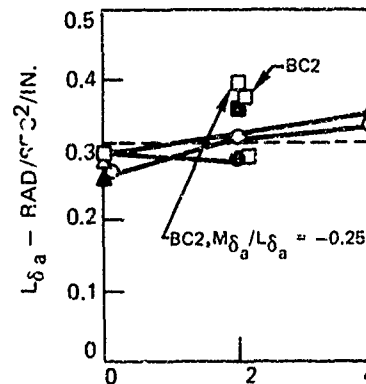


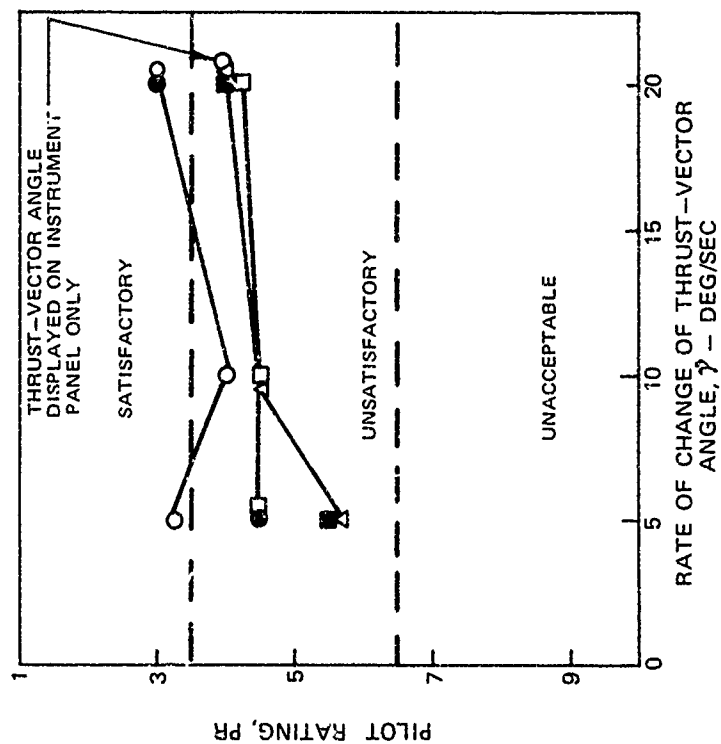
Figure 25. Effects of Inter-Axis Motion Coupling on Pilot Rating and Control Sensitivities

| LEVEL # | 1 | 2 |
|----------------|-------|-------|
| BASIC CONF. | BC1 | BC4 |
| SIMULATOR MODE | FB MB | FB MB |
| SYMBOL | ○ ● □ | △ |

THRUST VECTOR ANGLE, γ , DISPLAYED ON CONTACT ANALOG AND INSTRUMENT PANEL UNLESS NOTED OTHERWISE

* SEE NOTE ON LEVELS SHOWN ON FIG. 20.

(a) THUMB-SWITCH THRUST-VECTOR CONTROL AND CONTROL-STICK ATTITUDE CONTROL



(b) CONTROL-STICK THRUST-VECTOR CONTROL AND THUMB-SWITCH ATTITUDE CONTROL

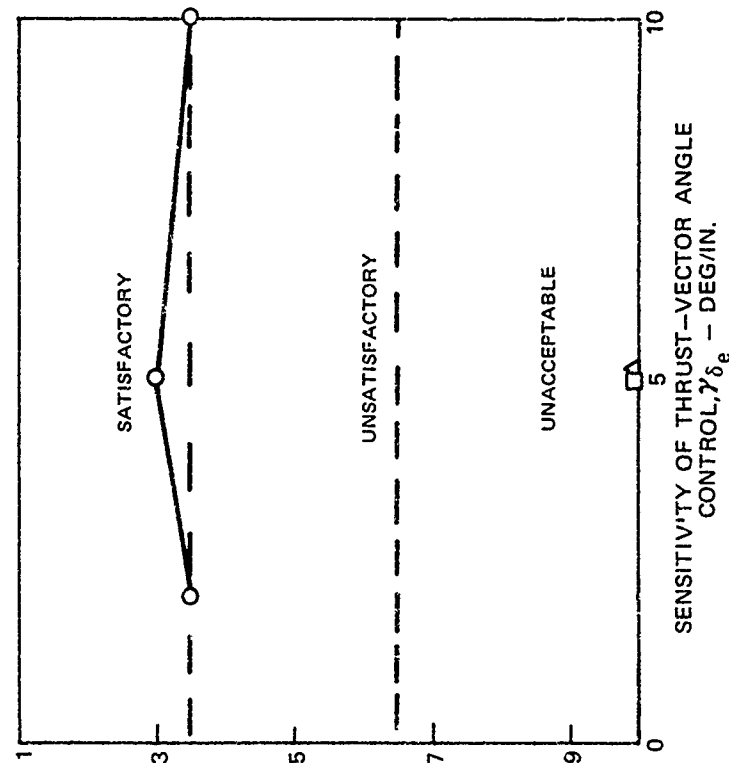


Figure 26. Pilot Rating Results from the Study of Independent Thrust-Vector Control

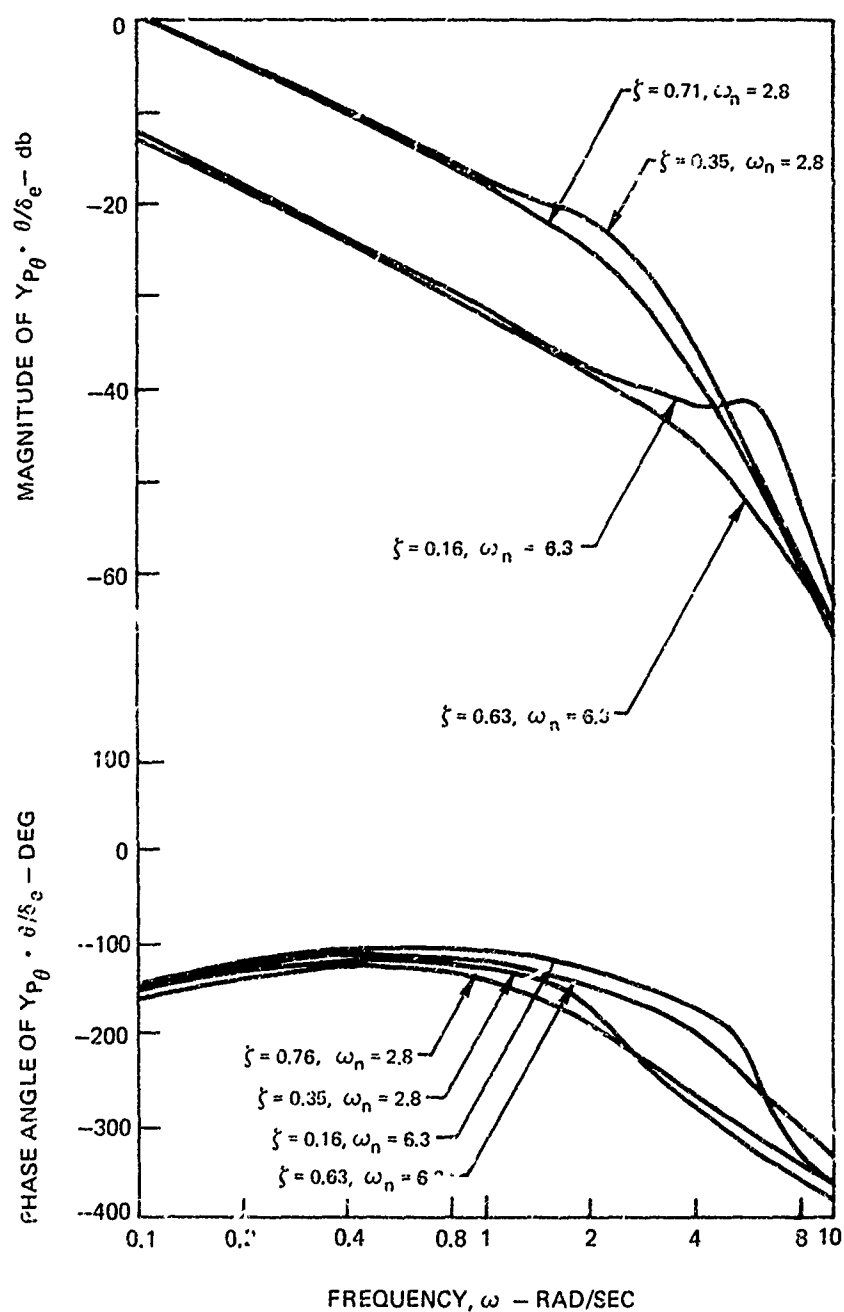
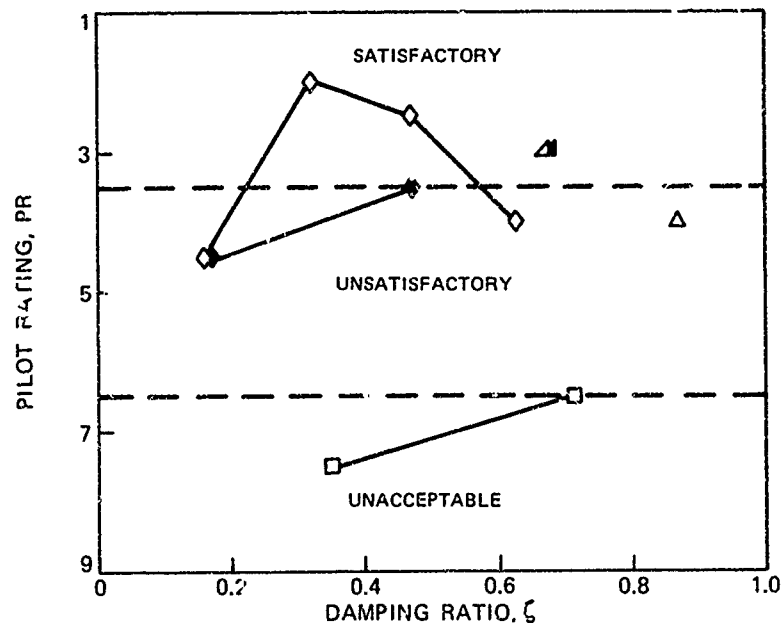


Figure 27. Magnitude and Phase Characteristics for Pilot-Pitch (Roll) Attitude Open-Loop Dynamics with Rate-Command/Attitude-Hold Control

(a) SPEED-STABILITY AND DRAG PARAMETERS OF CONFIGURATION BCI

| NATURAL FREQUENCY, ω_n | 2.90 | | 3.44 | | 6.30 | | 7.40 | |
|-------------------------------|-----------|----------------|-------------|------------------|------------|-----------------|-----------------|----------------------|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL | \square | \blacksquare | \triangle | \blacktriangle | \diamond | \blacklozenge | \triangleleft | \blacktriangleleft |



(b) SPEED-STABILITY AND DRAG PARAMETERS OF CONFIGURATION EC4

| NATURAL FREQUENCY, ω_n | 4.0 | | 5.0 | | 7.4 | |
|-------------------------------|---------|-----------|-----------|----------------|-------------|------------------|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | \circ | \bullet | \square | \blacksquare | \triangle | \blacktriangle |

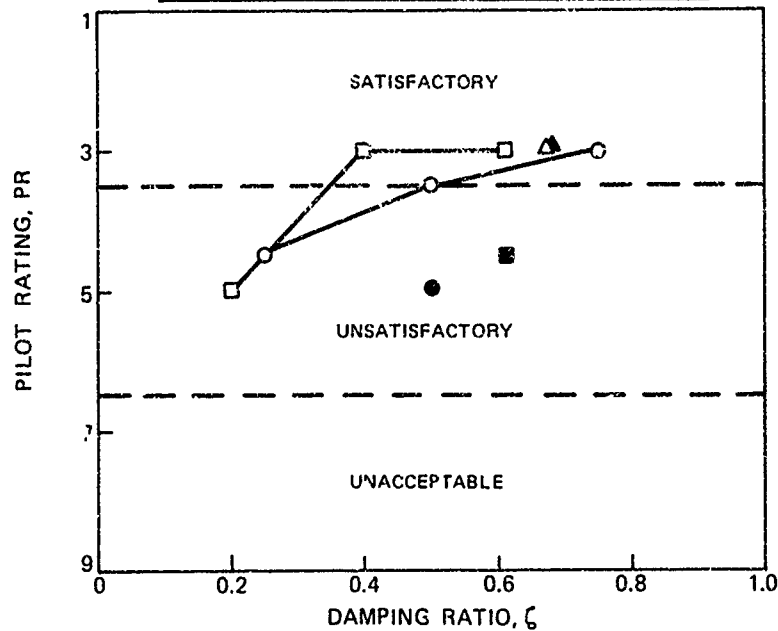








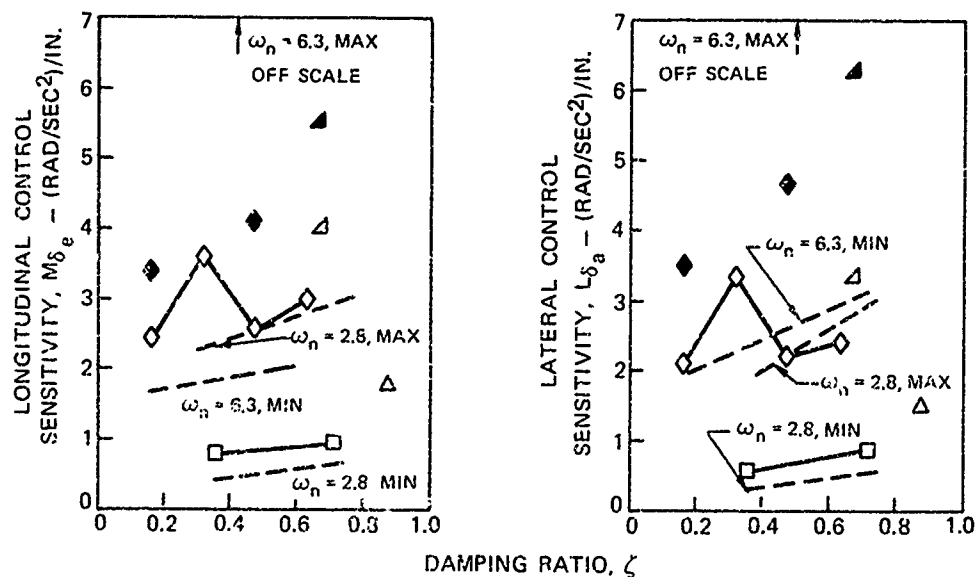


Figure 28. Pilot Rating Results for a Rate-Command/Attitude-Hold Control System

(a) SPEED-STABILITY AND DRAG PARAMETERS OF CONFIGURATION BC1

| NATURAL FREQUENCY, ω_n | 2.80 | | 3.44 | | 6.30 | | 7.40 | |
|-------------------------------|---|---|---|---|---|---|---|---|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL |  |  |  |  |  |  |  |  |

DASHED LINES SHOW MIL-F-83300 BOUNDARIES. SEE NOTE ON FIG. 12.



(b) SPEED-STABILITY AND DRAG PARAMETERS OF CONFIGURATION BC4

| | | | | | | |
|-------------------------------|-----|----|-----|----|-----|----|
| NATURAL FREQUENCY, ω_n | 4.0 | | 5.0 | | 7.4 | |
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ |

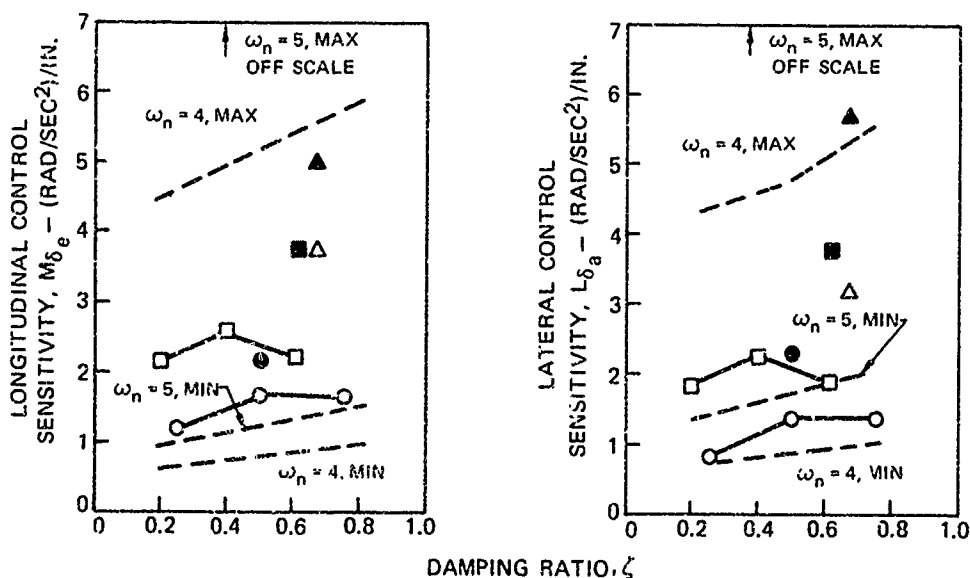


Figure 29. Control Sensitivities from the Study of Rate-Command/Attitude-Hold Control

| RMS TURBULENCE INTENSITY, FT/SEC | 3.4 | 5.8 | 8.2 |
|-------------------------------------|-----|-----|-----|
| SYMBOL | O | □ | △ |

CONFIGURATION BCI $M_{0.9} = -L_{0.9} = 0.33$ LEVEL 1*

* LEVEL APPLIES TO BASIC CONFIGURATION ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

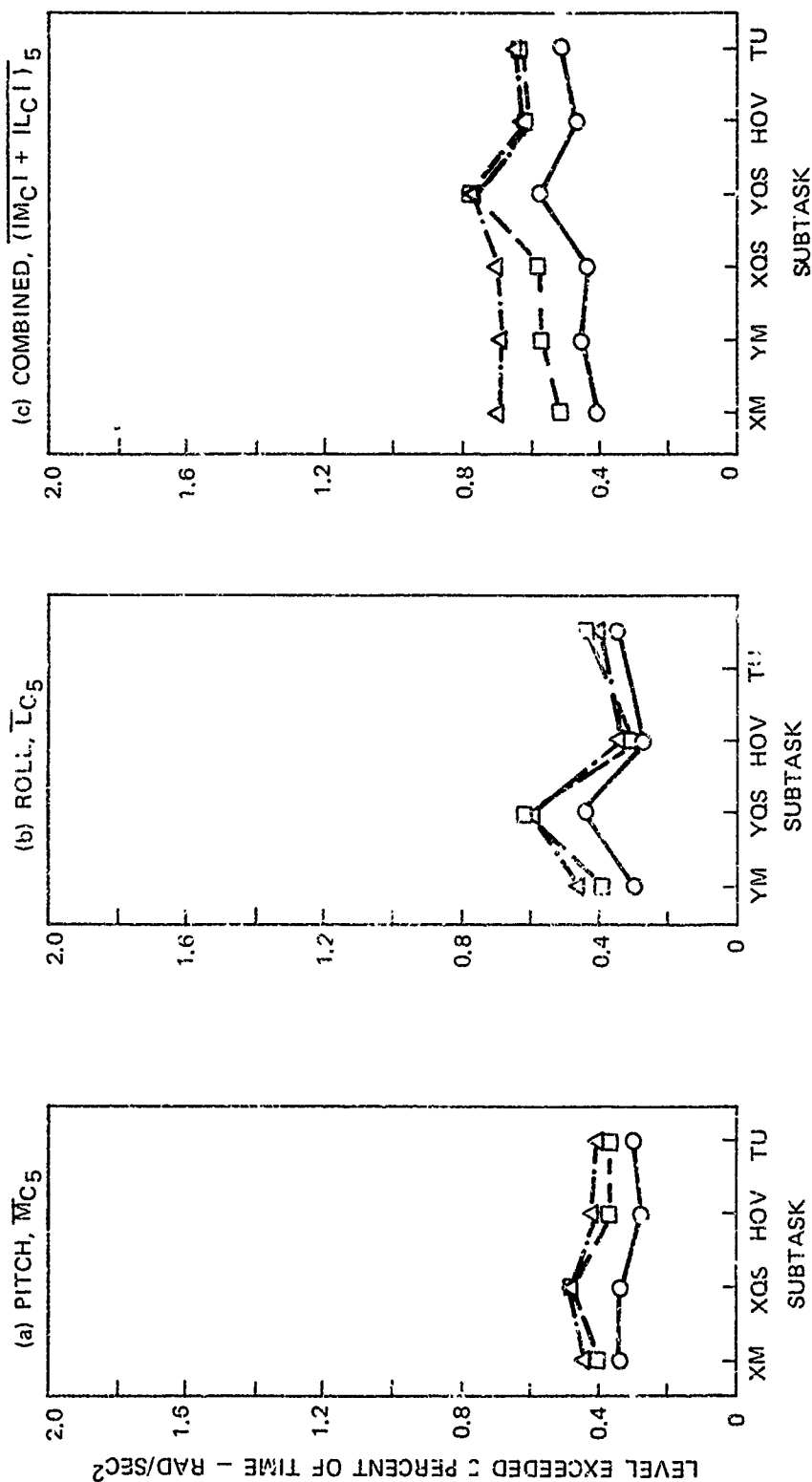


FIGURE 30. Effect of Turbulence on Five-Percent Exceedance Moment Level for a V/STOL Configuration with Small Response to Turbulence

| | | | |
|-------------------------------------|-----|-----|-----|
| RMS TURBULENCE INTENSITY, FT/SEC | 3.4 | 5.8 | 8.2 |
| SYMBOL | O | □ | △ |

CONFIGURATION BC6 $M_{10}g = -L_{10}g = 1.0$ LEVEL 2*

* LEVEL APPLIES TO BASIC CONFIGURATION ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

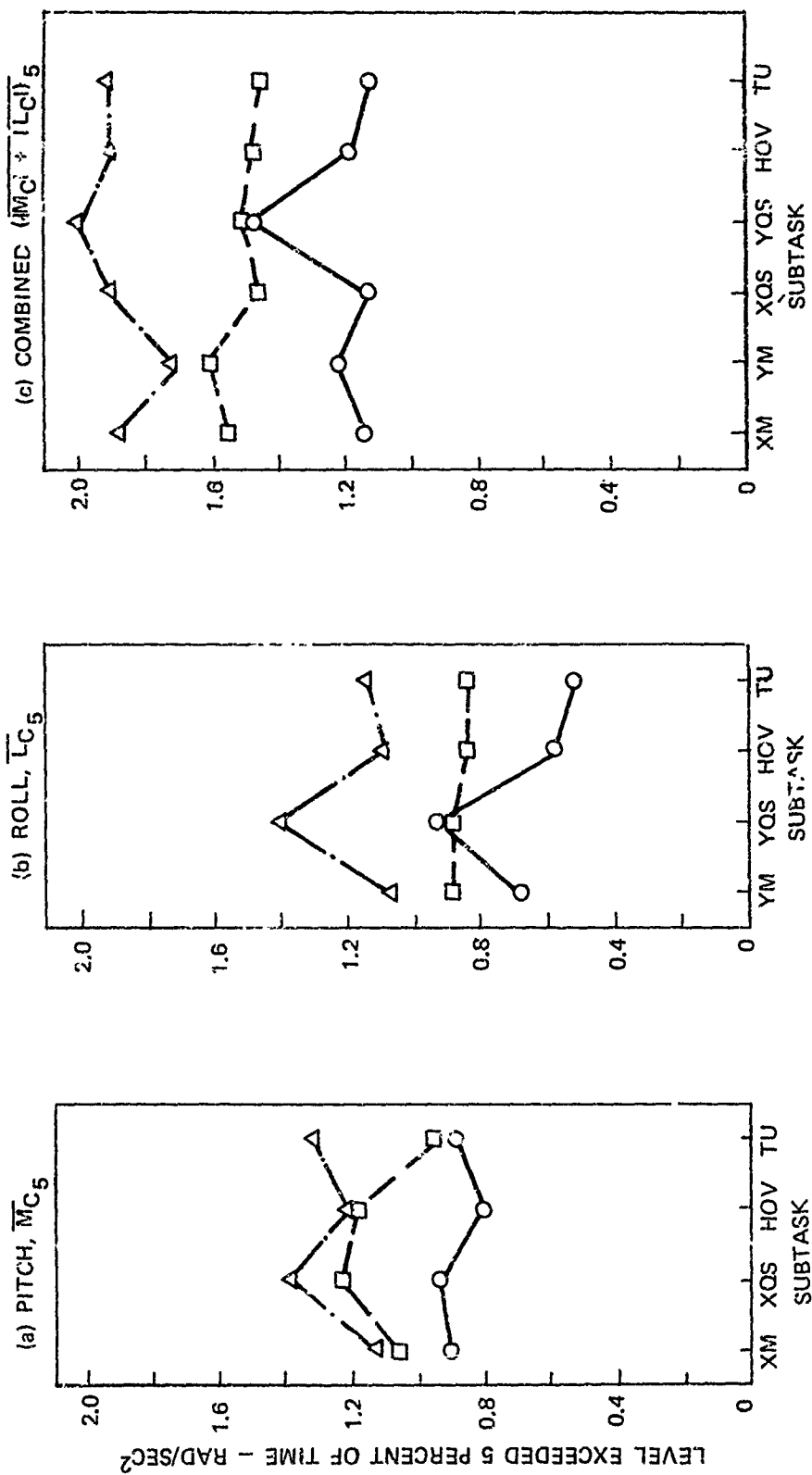


FIGURE 31. Effect of Turbulence on Five-Percent Exceedance Moment Level for a V/STOL Configuration with Large Response to Turbulence

| BASIC CONF. | BC5 | BC4 |
|--|------|-----|
| $M_{\dot{\theta}} = -L_{\dot{\theta}}$ | 0.33 | 1.0 |
| SYMBOL | ○ | □ |

BC5, BC4 LEVEL 1 CONFIGURATIONS $Q_{u_g} = Q_{v_g} = 3.4 \text{ FT/SEC}$

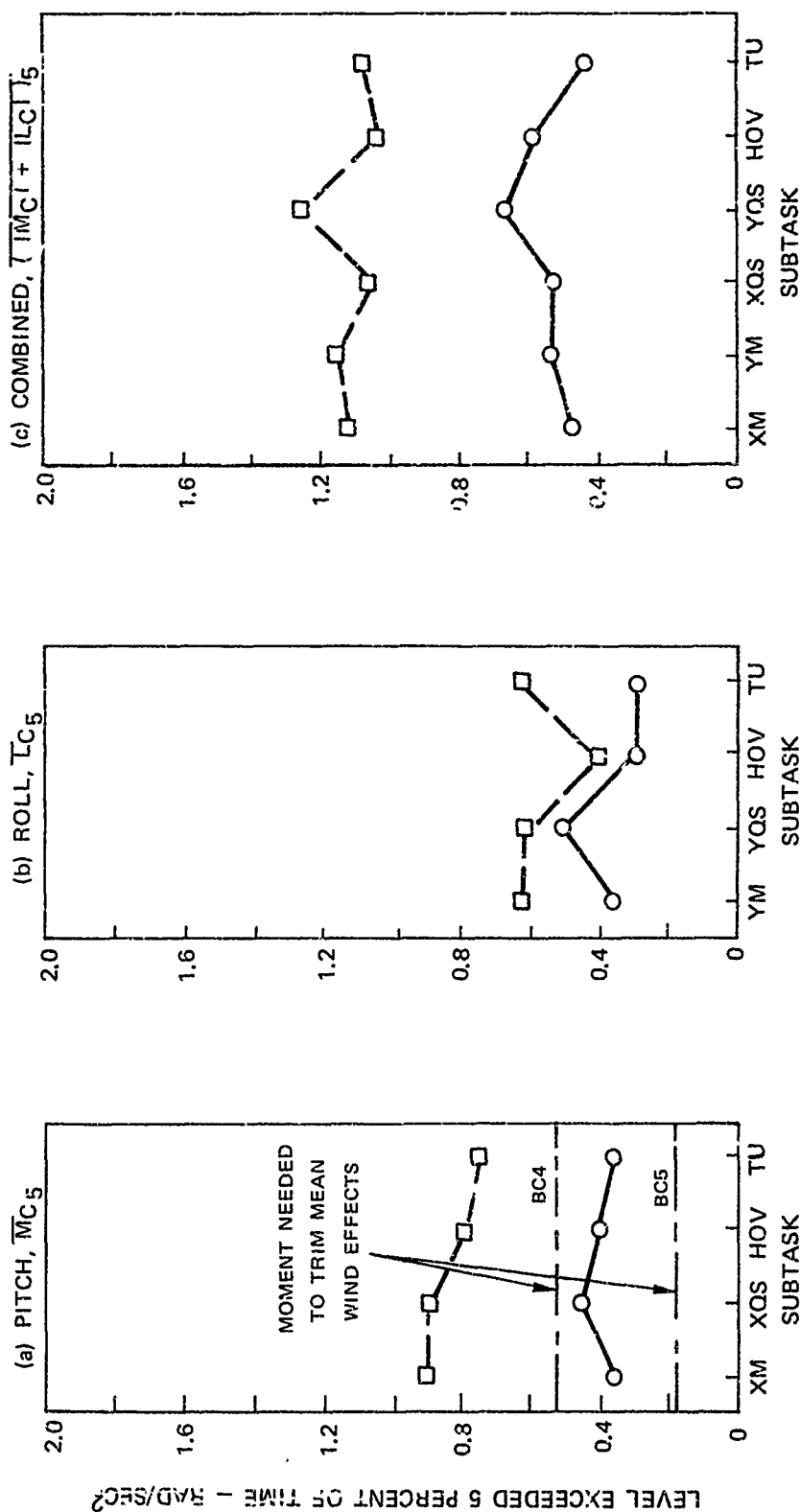


FIGURE 32. Five-Percent Exceedance Moment Levels Showing the Effect of Aircraft Speed-Stability Parameters

| BASIC CONF. | BC1 | BC5 |
|-------------|-------|-------|
| $X_u = Y_v$ | -0.05 | -0.20 |
| SYMBOL | O | □ |

BC1, BC5 LEVEL 1 CONFIGURATIONS $Q_{U_g} = Q_{V_g} = 3.4 \text{ FT/SEC}$

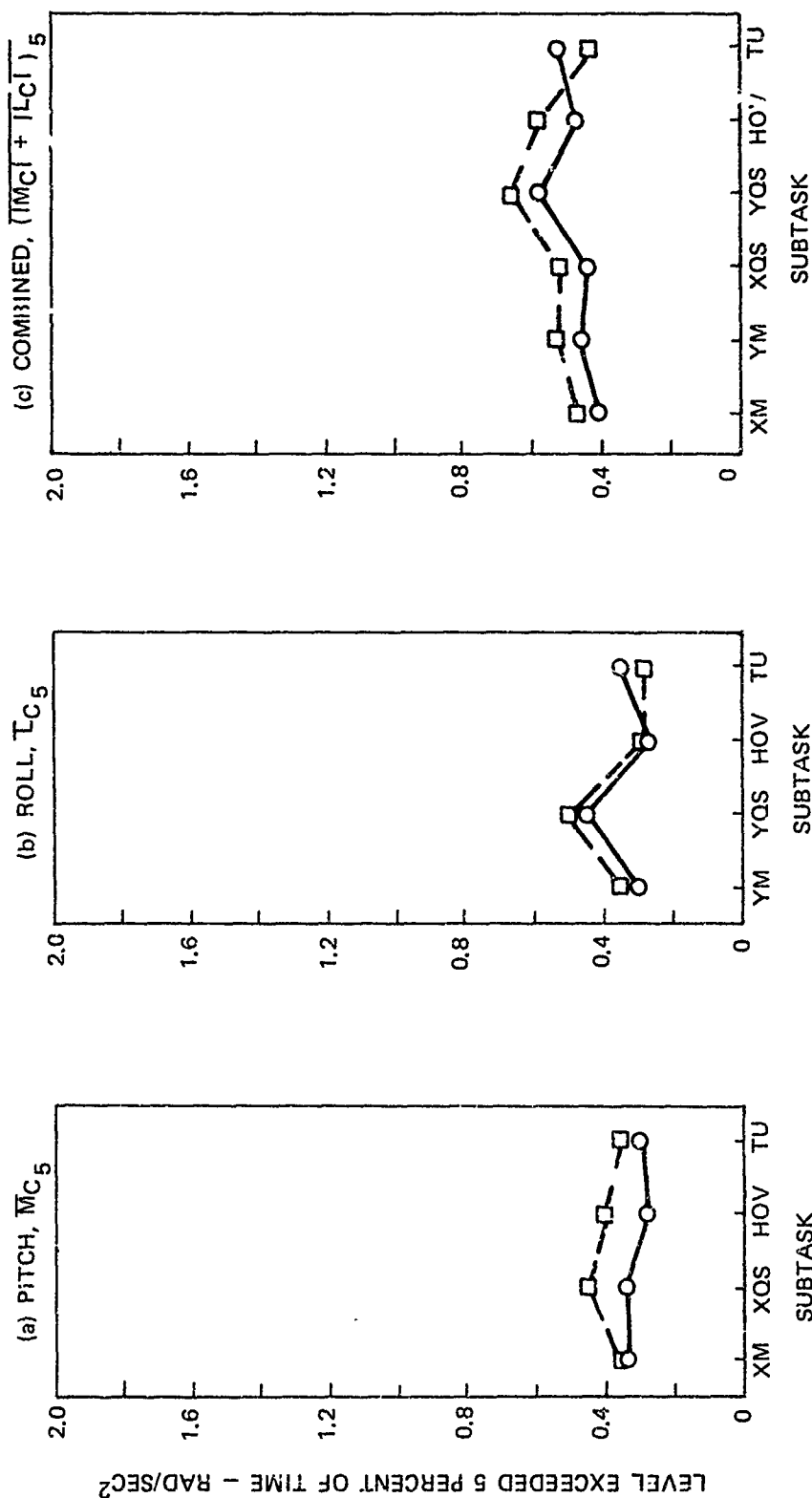


FIGURE 33. Five-Percent Exceedance Moment Levels for V/STOL Configurations Having Different Drag Parameters

| LEVEL | 1 | 2 | 3 |
|-------------|-----|-----|-----|
| BASIC CONF. | BC4 | BC2 | BC3 |
| SYMBOL | O | □ | △ |

$M_{Ug} = -L_{Ug} = 1.0$ FOR BC4, BC2, BC3 $\alpha_{Ug} = \alpha_{Ug} = 3.4$ FT/SEC

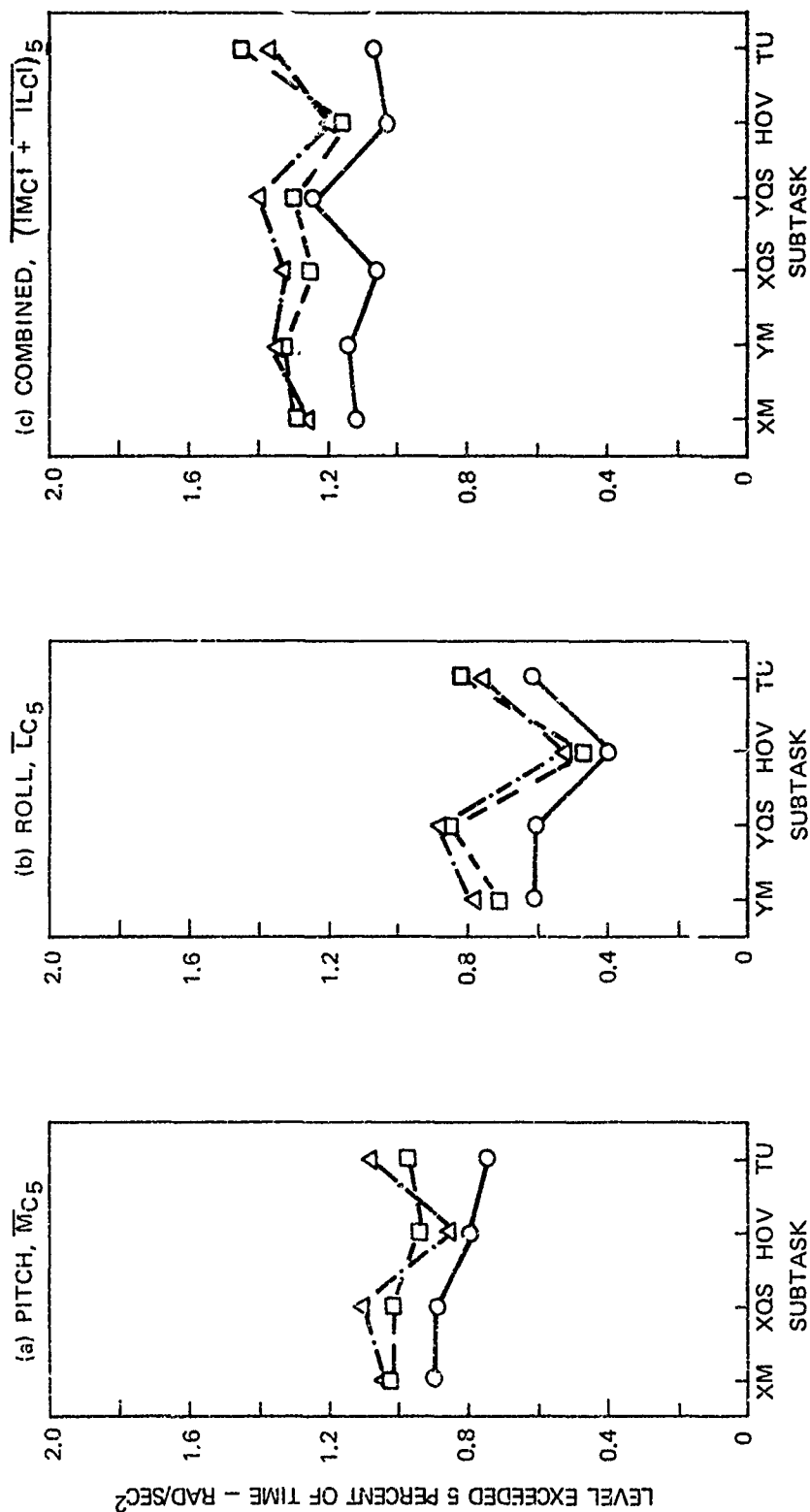


FIGURE 34. Five-Percent Moment Levels for Three V/STOL Configurations Exhibiting the Three MIL-F-83300 Levels of Flying Qualities

| | | | |
|-------------|---|-----|-----|
| CONTROL LAG | 0 | 0.3 | 0.6 |
| SYMBOL | O | □ | △ |

CONFIGURATION BC5 LEVEL 1* $M_{0.0} = L_{0.0} = 0.33$ $\sigma_{u_g} = \sigma_{v_g} = 3.4$ FT/SEC
 * LEVEL APPLIES TO BASIC CONFIGURATION ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN
 GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

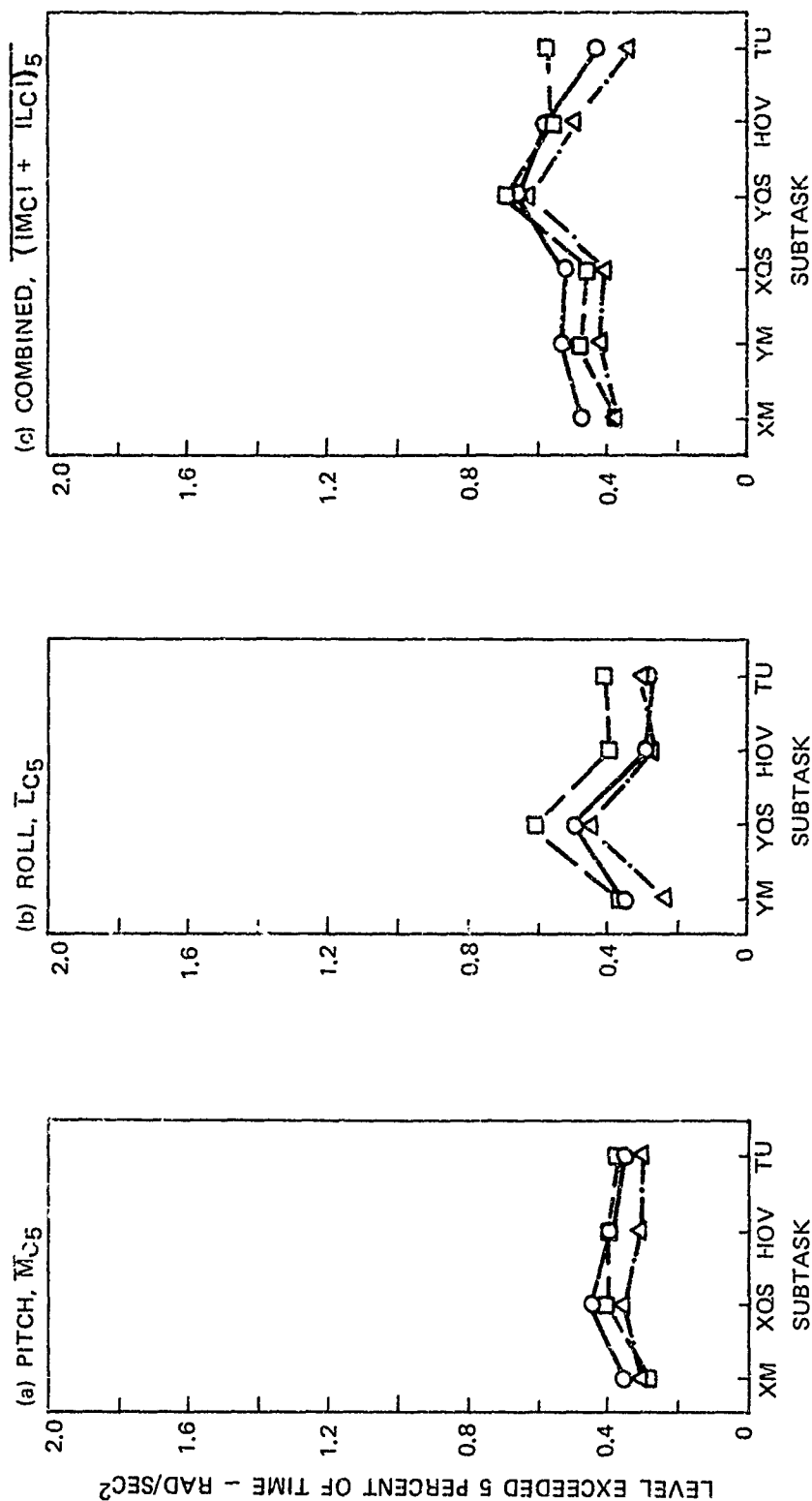


FIGURE 35. Effects of Control lags on Five-Percent Moment Levels for Configuration with Low Response to Turbulence

| CONTROL LAG | 0 | 0.3 | 0.6 |
|-------------|---|-----|-----|
| SYMBOL | O | □ | Δ |

CONFIGURATION BC4 LEVEL 1 * $M_{U0} = -L_{U0} = 1.0$ $\sigma_{U_g} = \sigma_{V_g} = 3.4$ FT/SEC

* LEVEL APPLIES TO BASIC CONFIGURATION ONLY. DUE TO PARAMETER VARIATIONS, THE LEVEL SHOWN GENERALLY DOES NOT DESCRIBE FLYING QUALITIES OF TEST CASES.

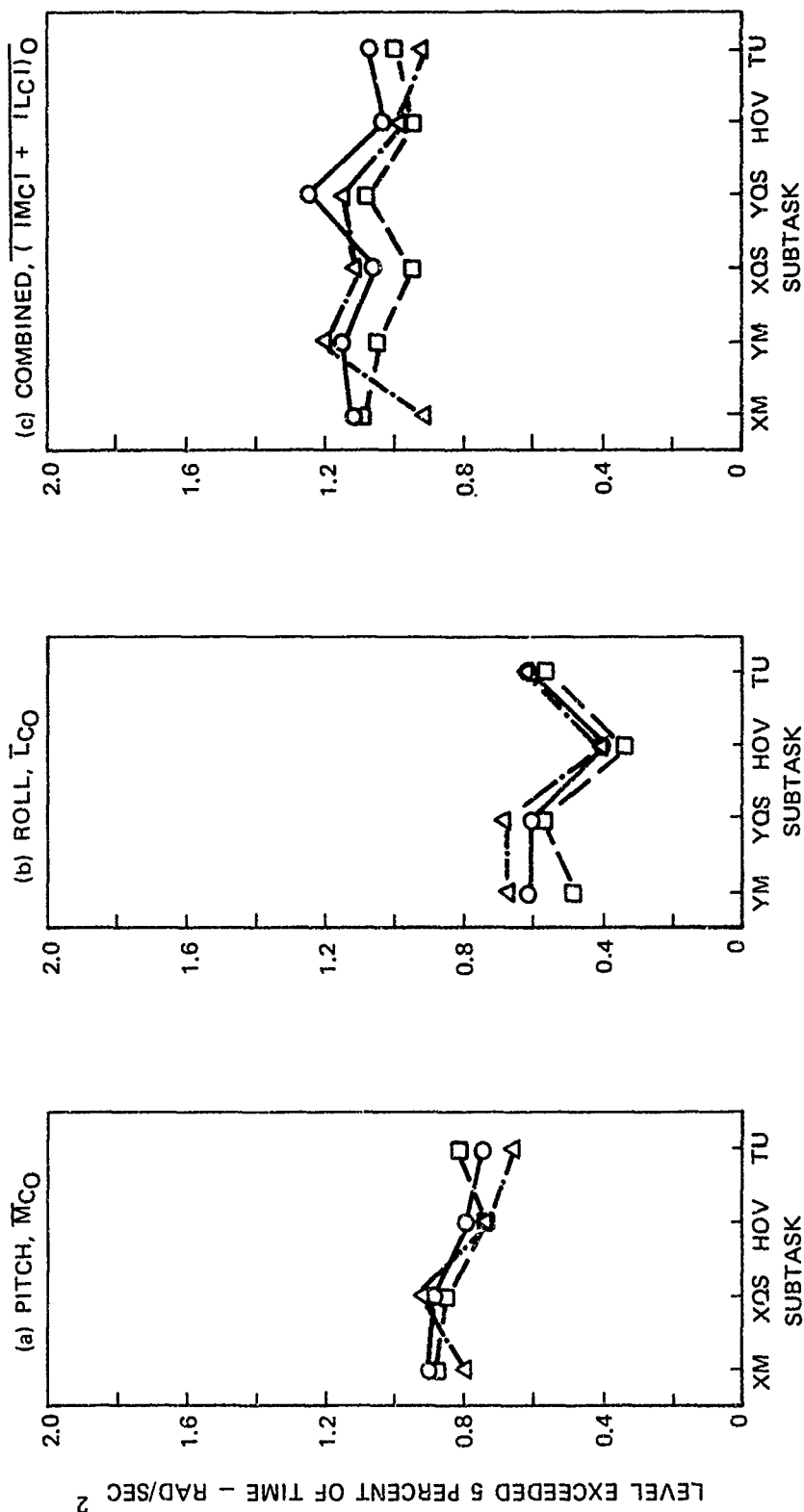


FIGURE 36. Effects of Control Lags on Five-Percent Moment Levels for Configuration with Moderate Response to Turbulence

| $M_{\delta_a} / L_{\delta_a} = -L_{\delta_e} / M_{\delta_e}$ | | 0 | | 0.25 | | 0.50 | |
|--|--|----|----|------|----|------|----|
| SIMULATOR MODE | | FB | MB | FB | MB | FB | MB |
| SYMBOL | | ○ | ● | □ | ■ | △ | ▲ |

CONFIGURATION BC1 CONTROL AND RATE COUPLING EFFECTS ADDITIVE (SEE FIG. 2E FOR EXPLANATION)

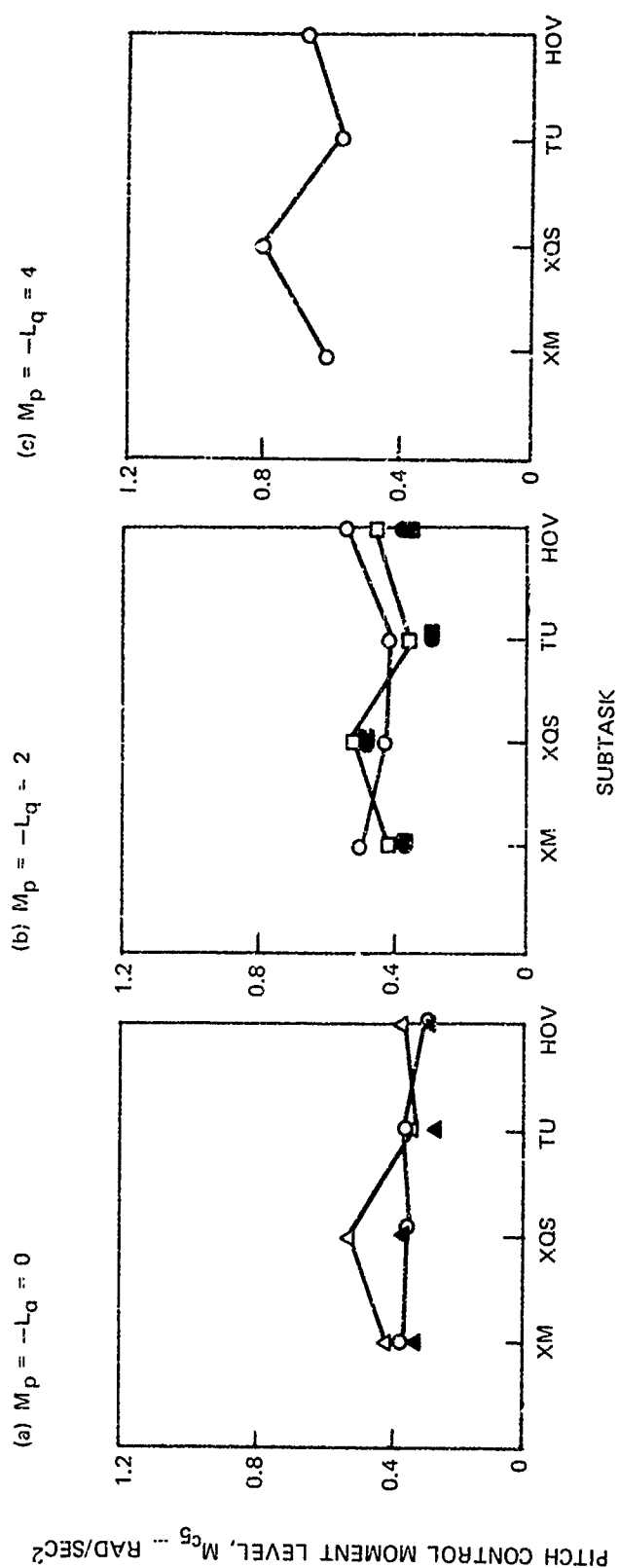


Figure 37. Effect of Rate and Control Coupling on Pitch 5-Percent Exceedance Control-Moment Level

| LEVEL | | 1 | | 2 | | 3 |
|-------------|--|------|------|------|------|------|
| BASIC CONF. | | BC 1 | BC 5 | BC 4 | BC 2 | BC 6 |
| SYMBOL | | ○ | □ | △ | ◇ | △ |
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| CONTROL MOMENT | $(M_{C1} + 1L_{C1})_5$ | $M_{C5} + L_{C5}$ | $\sqrt{M_{C5}^2 + L_{C5}^2}$ |
|----------------|------------------------|-------------------|------------------------------|
| SYMBOL | O | □ | △ |

HOVER SUBTASK

$$Q_{u_9} = Q_{u_9} = 3.4 \text{ FT/SEC}$$

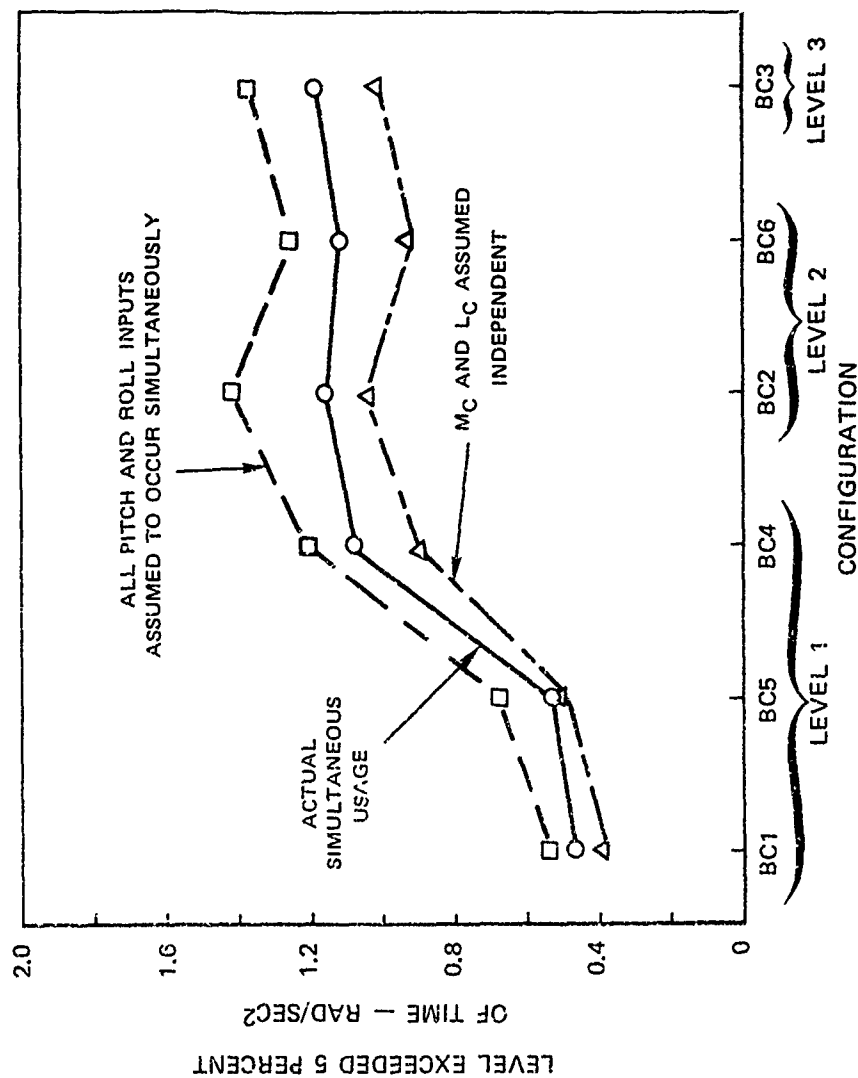
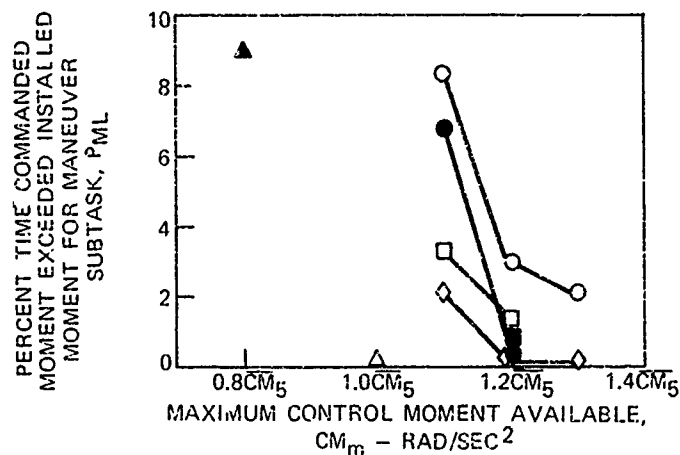


Figure 39. Comparison of Actual Five-Percent Simultaneous Usage Moment Levels for Hover with Hypothetical Maximum and Minimum Values for these Levels

| BASIC CONF. | BC1 | | BC4 | | BC5 | | BC6 | |
|----------------|-----|----|-----|----|-----|----|-----|----|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ | ◇ | ◆ |

\overline{CM}_5 : AVERAGED 5-PERCENT EXCEEDANCE MOMENT LEVELS FOR PITCH AND ROLL WITH UNLIMITED CONTROL MOMENT AVAILABLE

(a) PITCH CONTROL



(b) ROLL CONTROL

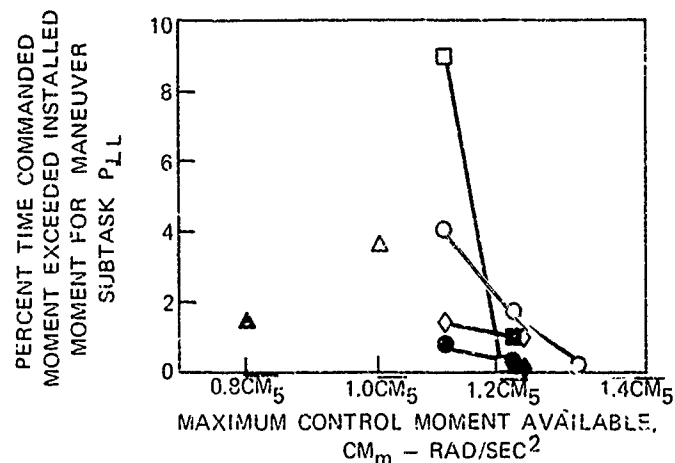
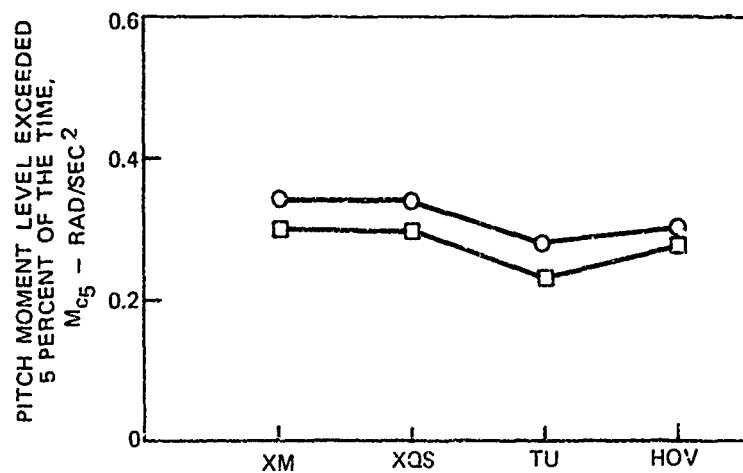


Figure 40. Percent Time Total Moment Command Exceeded Installed Pitch and Roll Control Moments for Flight with Limited Available Moments

| TYPE OF POSITION CONTROL | CONVENTIONAL | INDEPENDENT THRUST-VECTOR CONTROL |
|--------------------------|--------------|-----------------------------------|
| SYMBOL | ○ | □ |

FIXED BASE
THUMB-SWITCH THRUST-VECTOR CONTROL, $\dot{\gamma} = 20$ DEG/SEC, AND CONTROL-STICK ATTITUDE CONTROL FOR INDEPENDENT THRUST-VECTOR CONTROL

(a) CONFIGURATION BC1



(b) CONFIGURATION BC4

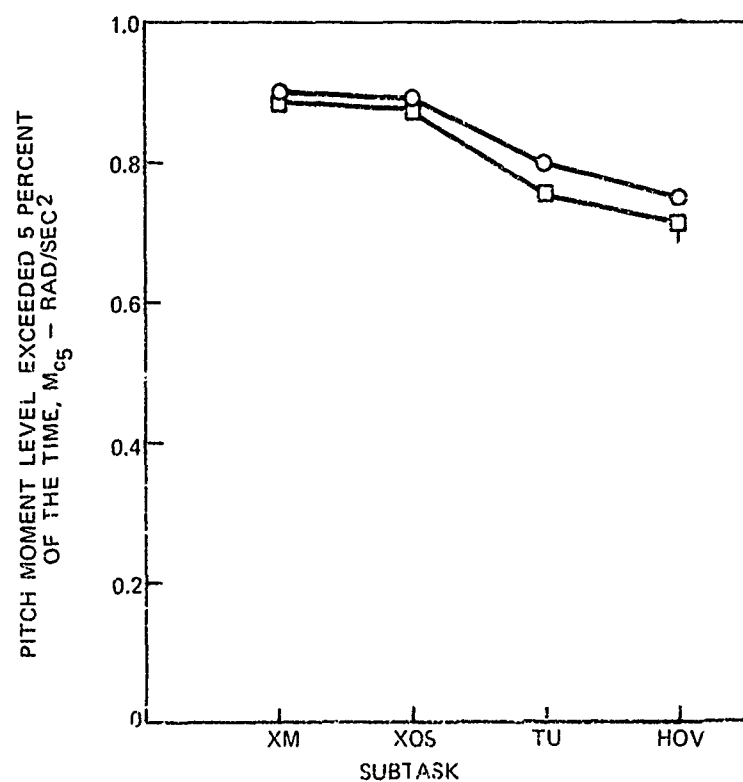
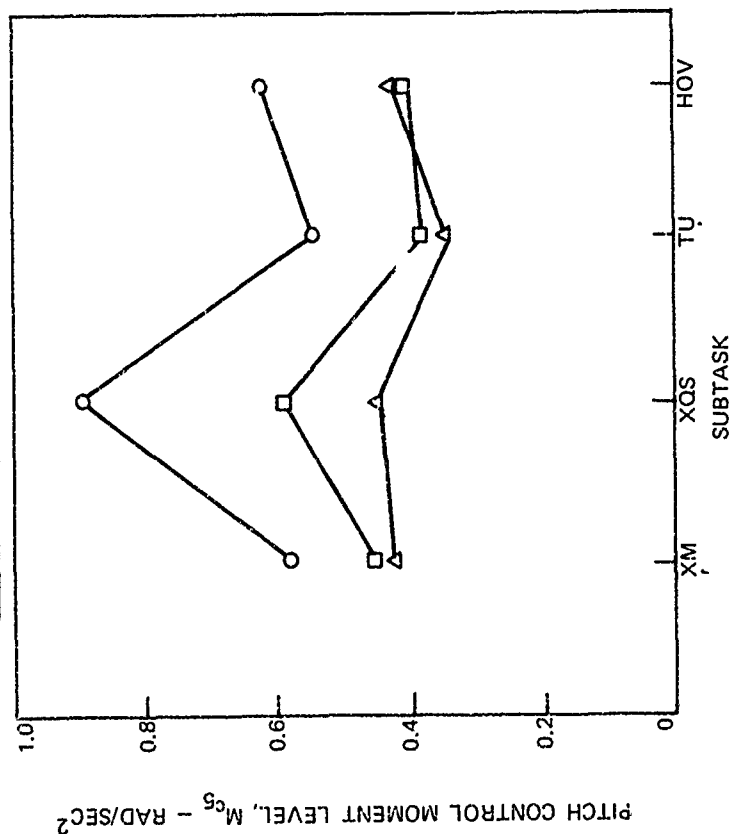


Figure 41. Comparison Between Pitch Control-Moment 5-Percent Exceedance Levels for Independent Thrust-Vector Control and Conventional Position Control

CONFIGURATION RC1

(a) $\omega_n = 2.8$ AND 3.4 RAD/SEC

| ω_n | | 2.8 | | 3.4 | |
|----------------|--|------|----|------|----|
| ξ | | 0.35 | | 0.71 | |
| SIMULATOR MODE | | FB | MB | FB | MB |
| SYMBOL | | ○ | ● | □ | ■ |



(b) $\omega_n = 6.3$ RAD/SEC

| ξ | | 0.16 | | 0.47 | |
|----------------|--|------|----|------|----|
| SIMULATOR MODE | | FB | MB | FB | MB |
| SYMBOL | | ○ | ● | □ | ■ |

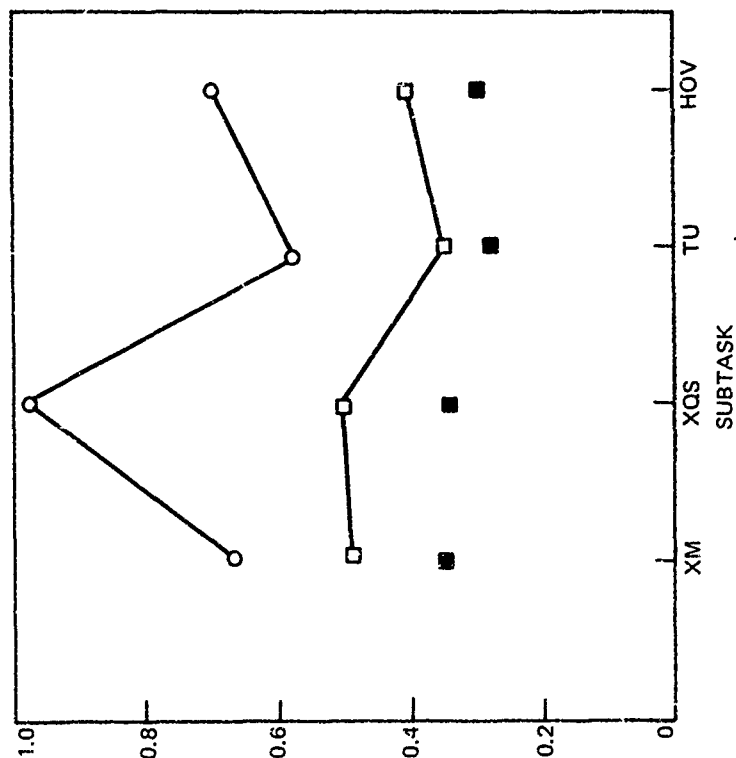
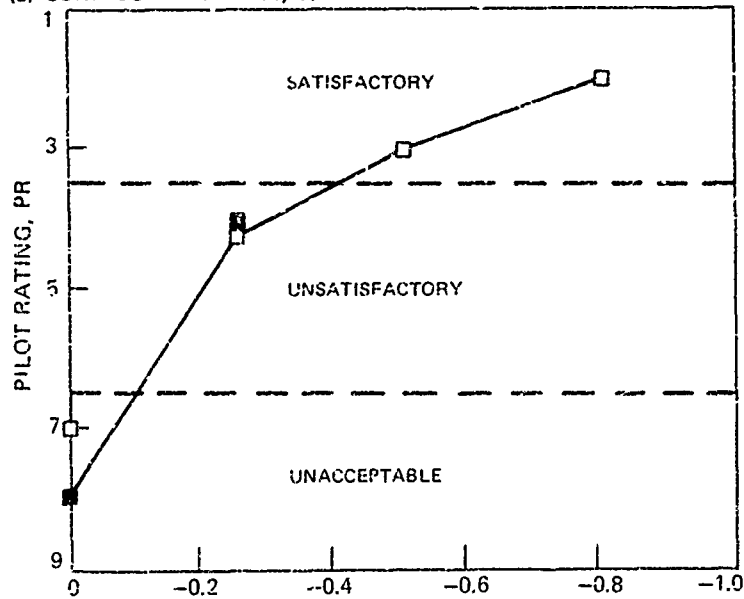


Figure 42. Five-Percent Pitch Control-Moment Exceedance Levels for Rate-Command/Attitude-Hold Control System

| PILOT | CALSPAN B* | UARL | |
|----------------|------------|------|----|
| SIMULATOR MODE | MB | FB | MB |
| SYMBOL | ● | □ | ■ |

* NO SIMULATED WINDS FOR CALSPAN PILOT EVALUATION

(a) CONFIGURATION BC1, $T/W > 1.15$



(b) CONFIGURATION BC4, $T/W > 1.15$

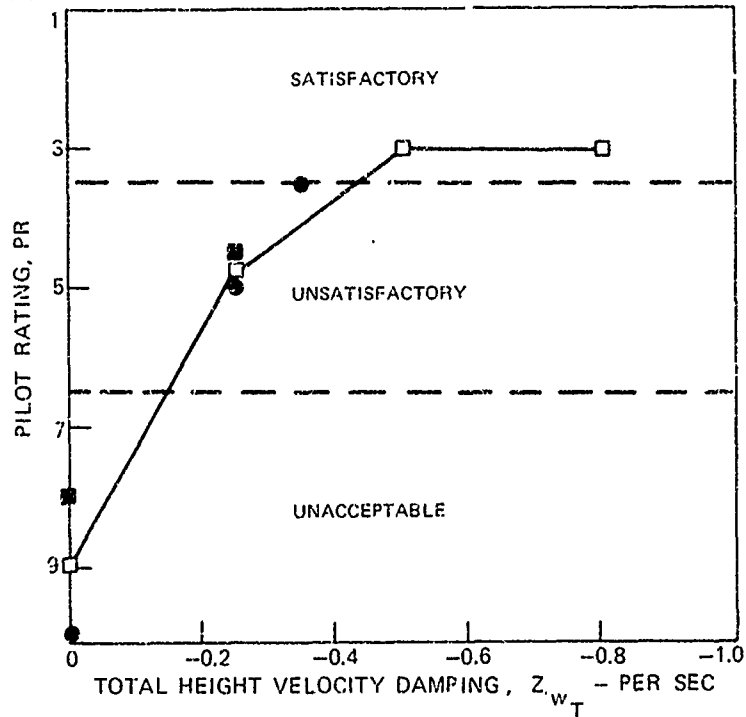


Figure 43. Change in Pilot Rating of Height Control with Height Velocity Damping

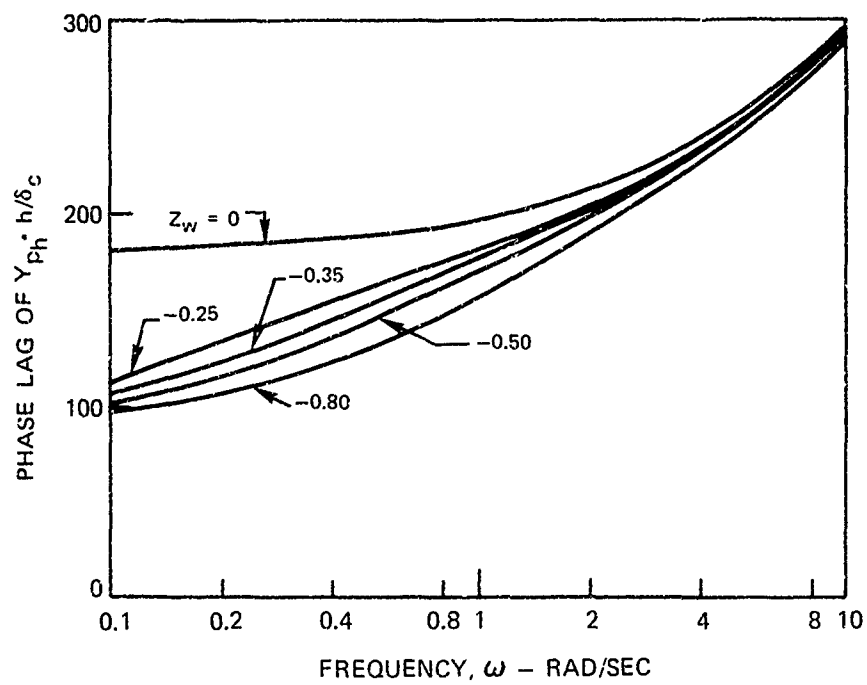
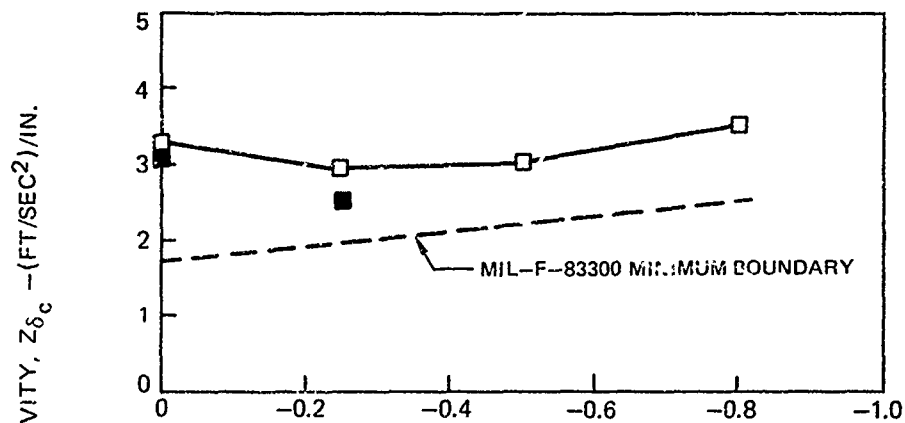


Figure 44. Phase Lags for Pilot-Height Open-Loop Dynamics at Several Z_w Levels

| SIMULATOR MODE | FB | MB |
|-------------------|----|----|
| SYMBOL | □ | ■ |

$T/W > 1.15$

(a) CONFIGURATION BC1



(b) CONFIGURATION BC4

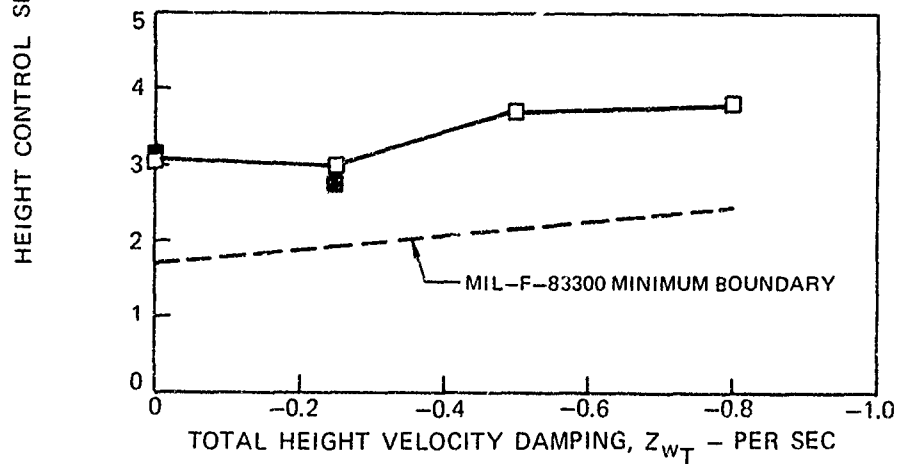


Figure 45. Height Control Sensitivity Results Showing the Effects of Height Velocity Damping

| TYPE OF DAMPING | $Z_{WT} = Z_{W_d} + Z_{W_s}$ $Z_{W_s} = Z_{W_0}$ | | | | $Z_{WT} = Z_{W_0}$ $Z_{W_0} = 0$ | | | | $Z_{WT} = Z_{W_s}$ $Z_{W_s} = 0$ | | | |
|-----------------|---|----|------|----|-------------------------------------|----|------|----|-------------------------------------|----|------|----|
| | CALSPAN B* | | UARL | | CALSPAN B* | | UARL | | CALSPAN B* | | UARL | |
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB | FB | MB | FB | MB | FB | MB |
| SYMBOL | O | ● | ○ | ● | □ | ■ | □ | ■ | △ | ▲ | △ | ▲ |

LEVEL BOUNDARIES FROM MIL-F-83300

Z_{WT} = TOTAL HEIGHT VELOCITY DAMPING Z_{W_0} = AERODYNAMIC HEIGHT VELOCITY DAMPING Z_{W_s} = SAS HEIGHT VELOCITY DAMPING
 $*U_m = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0$ FT/SEC FOR CALSPAN PILOT EVALUATIONS

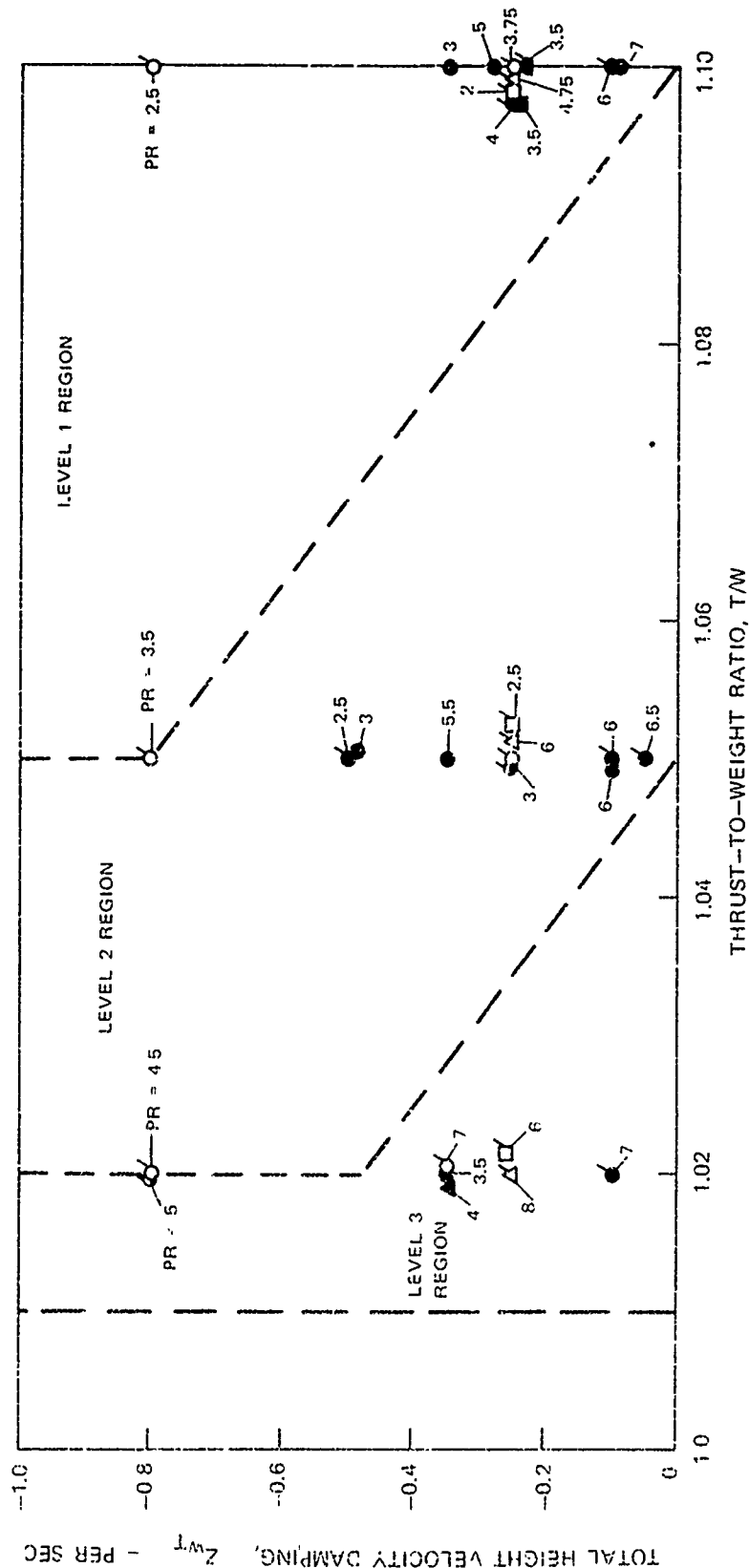


Figure 46. Pilot Rating Results Showing the Interaction Between Height Velocity Damping and Thrust-to-Weight Ratio

| T/W | 1.02 | | 1.05 | | 1.10 | |
|----------------|------|----|------|----|------|----|
| SIMULATOR MODE | FB | MB | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ | △ | ▲ |

CONFIGURATION BC1

$$Z_{WT} = Z_{Wd} + Z_{Ws} = -0.25 \text{ FOR ALL CASES}$$

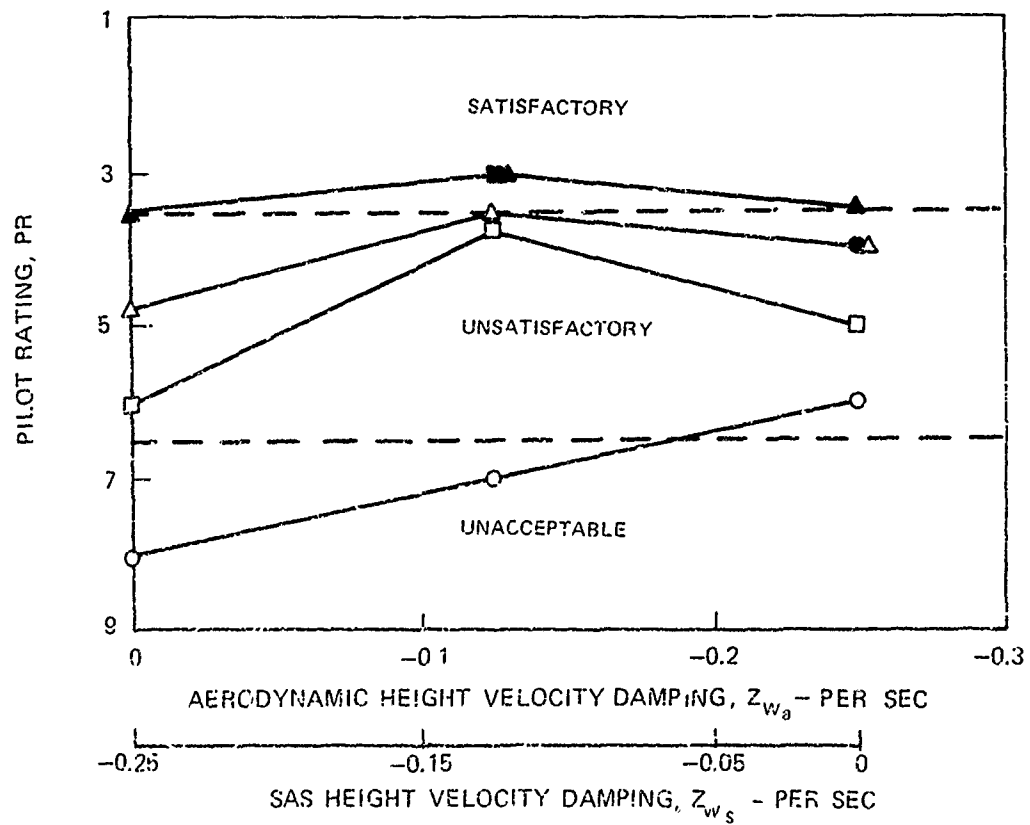


Figure 47. Comparison of Pilot Rating Results for Aerodynamic Versus Stability Augmentation System Height Velocity Damping

| LEVEL OF Z_{WT} | - 0.25 | | -0.35 | | - 0.50 | |
|-------------------|--------|----|-------|-----|--------|----|
| DELAY, d_h | 0 | | 0 | 0.1 | 0 | |
| SIMULATOR MODE | FB | MB | FB | FB | FB | MB |
| SYMBOL | O | ● | □ | ◻ | △ | ▲ |

CONFIGURATION BC1

T/W = 1.05

$$Z_{WT} = Z_{W_2} + Z_{W_5} \text{ WHERE } Z_{W_2} = Z_{W_5}$$

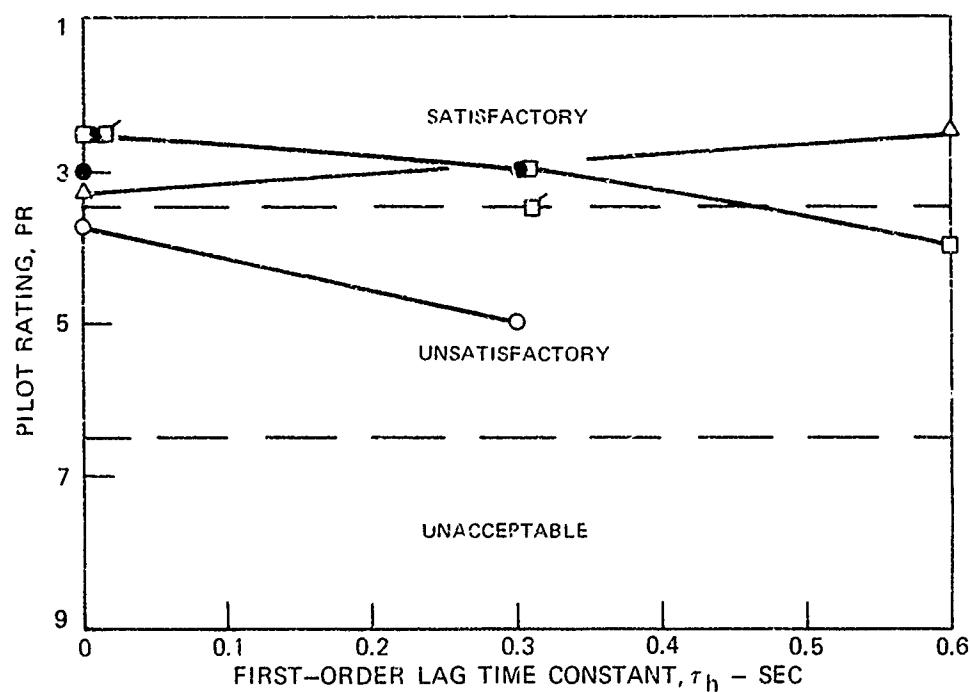


Figure 48. Pilot Rating Results Showing the Interaction Between First-Order Lag Time Constant and Height Velocity Damping

| PILOT | B | | | |
|----------------|------|----|------|----|
| $\Delta T/W$ | 0.13 | | 0.28 | |
| SIMULATOR MODE | FB | MB | FB | MB |
| SYMBOL | O | ● | □ | ■ |

CONFIGURATION BC1 $Z_{wT} = Z_{ws} = -0.35$ $T/W = 1.02$

$\Delta T/W$: MAXIMUM THRUST INCREMENT AVAILABLE THROUGH STORED ENERGY

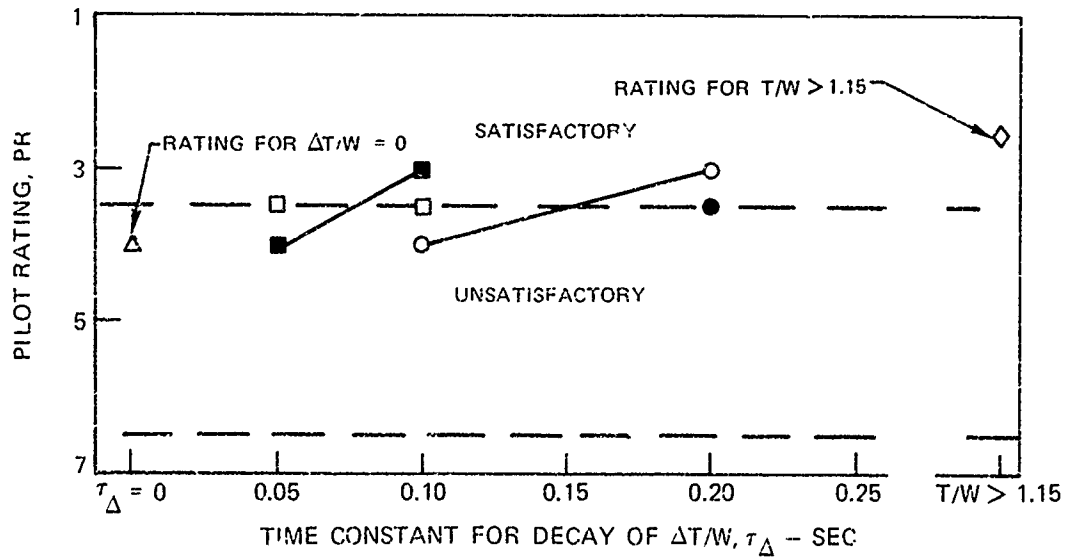


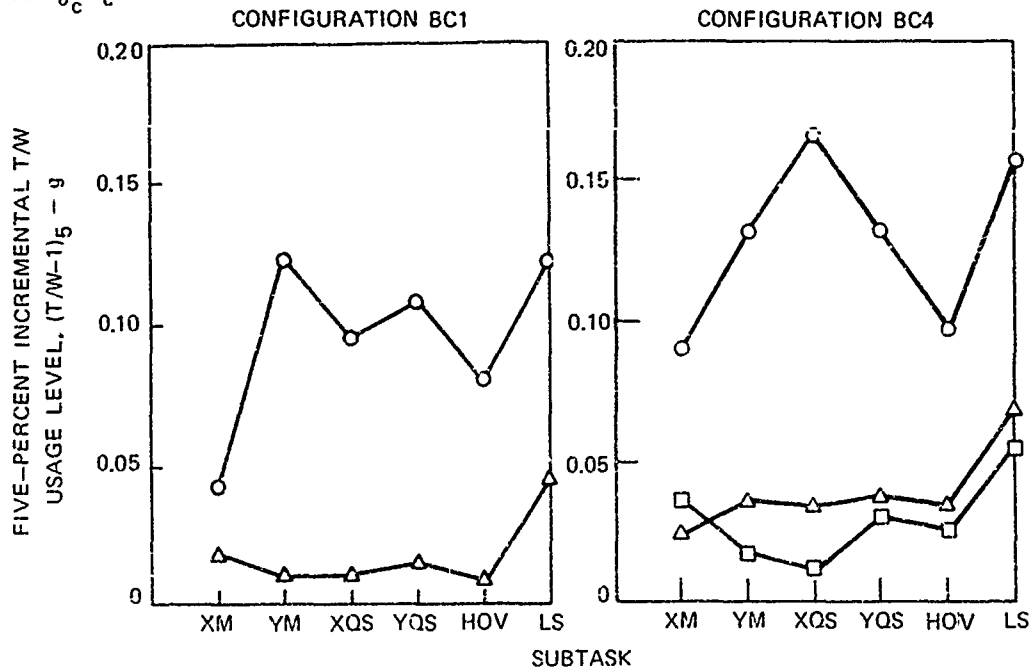
Figure 49. Change in Pilot Ratings Which Results from Incremental Thrust Available Through Stored Energy

| LEVEL OF Z_{wT} | 0 | -0.25 | -0.50 |
|-------------------|---|-------|-------|
| SYMBOL | ○ | □ | △ |

$$Z_{wT} = Z_{wa} + Z_{ws} \text{ WHERE } Z_{wa} = Z_{ws}$$

$$\gamma/W > 1.15$$

(a) $Z_{\delta_c} \cdot \delta_c$



(b) $Z_{\delta_c} \cdot \delta_c + Z_{ws} \cdot w$

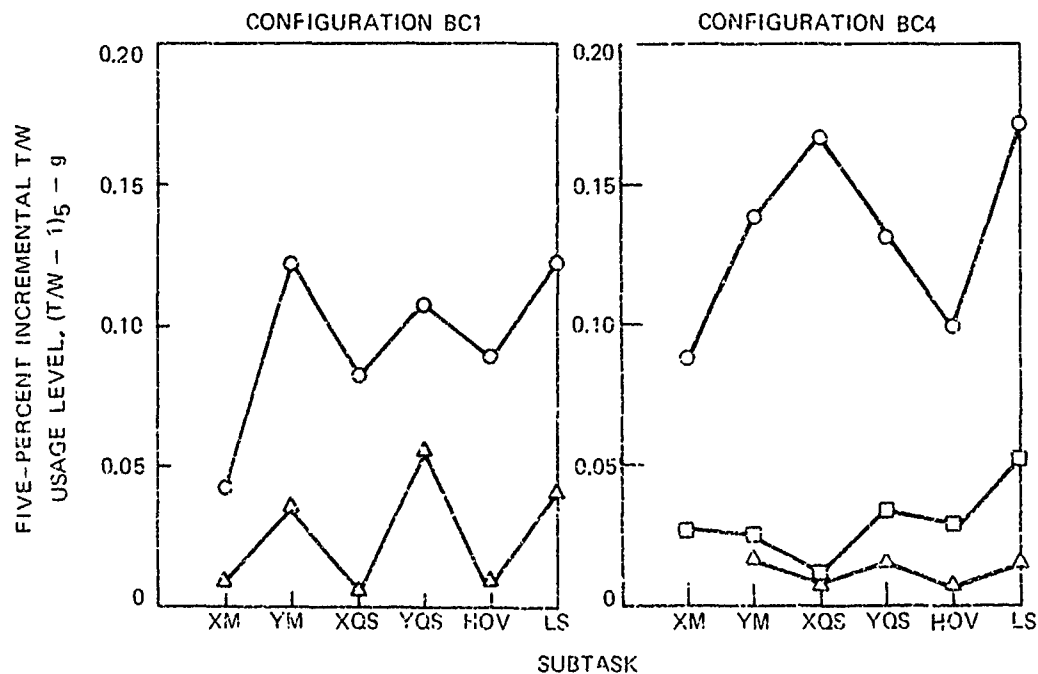


Figure 50. Effect of Z_{wT} on Incremental Thrust 5-Percent Exceedance Levels, $(T/W-1)_5$, Computed for Increased Thrust Commands

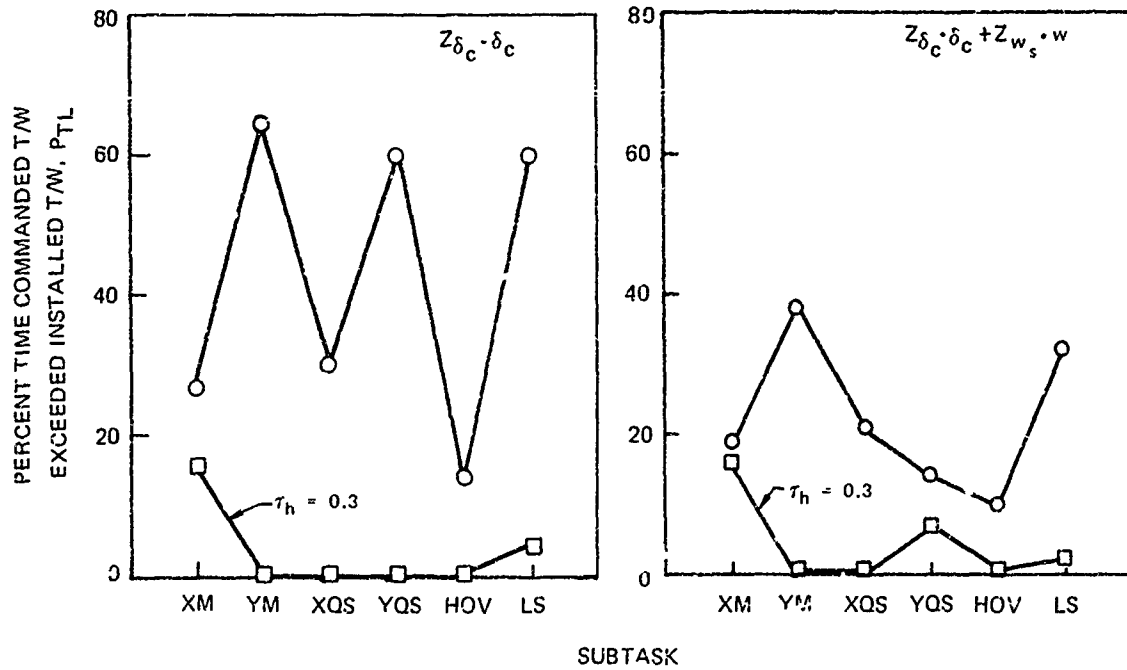
| | | |
|--------|------|------|
| T/W | 1.02 | 1.05 |
| SYMBOL | ○ | □ |

CONFIGURATION BCI

$$Z_{WT} = Z_{Vg} + Z_{Ws} \quad Z_{Wg} = Z_{Ws}$$

$\tau_h = 0$ EXCEPT WHERE INDICATED

(a) $Z_{WT} = -0.25$



(b) $Z_{WT} = -0.50$

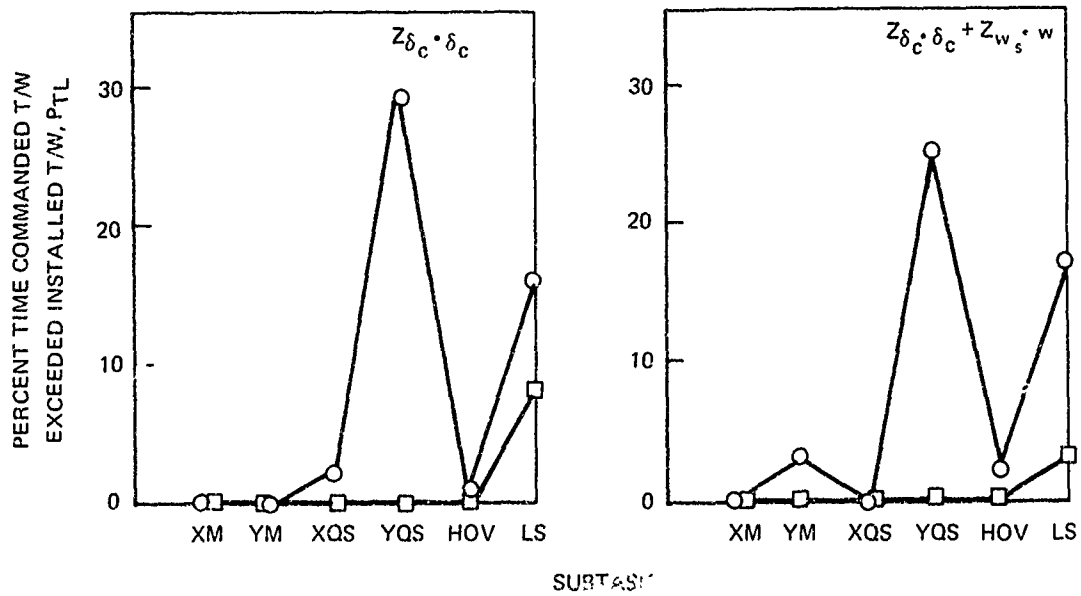


Figure 51. Percent Time Installed Thrust-to-Weight Ratio Limits Exceeded

| LAG TIME CONSTANT | 0 | 0.3 |
|-------------------|---|-----|
| SYMBOL | ○ | □ |

CONFIGURATION BCI T/W = 1.10 FIXED BASE

$$Z_{w_T} = Z_{w_a} + Z_{w_s} = -0.25 \text{ WHERE } Z_{w_a} = Z_{w_s}$$

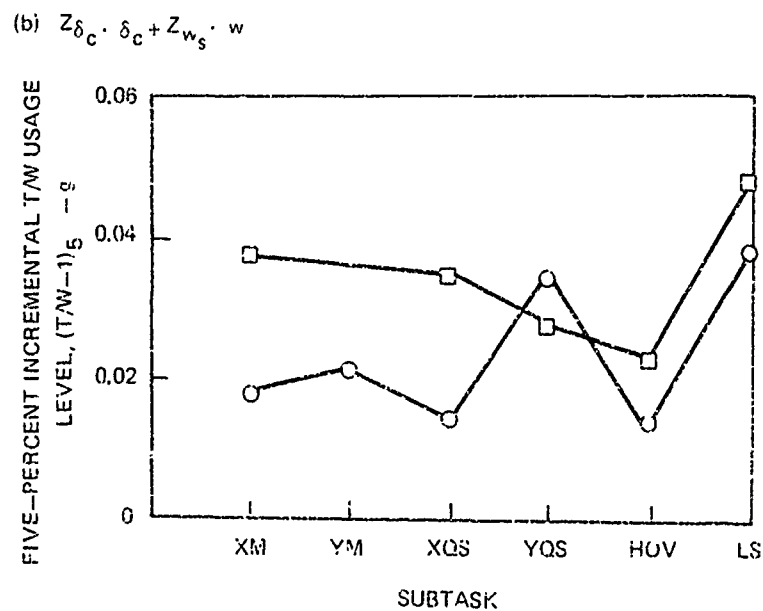
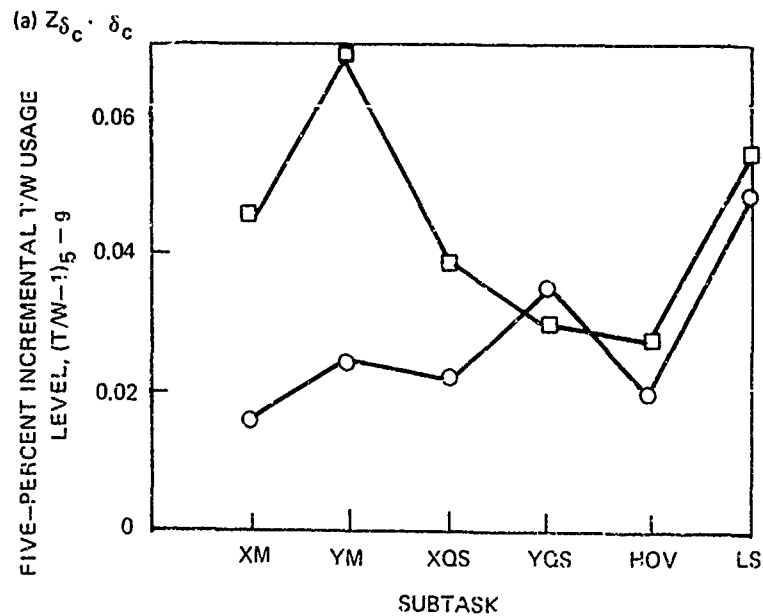
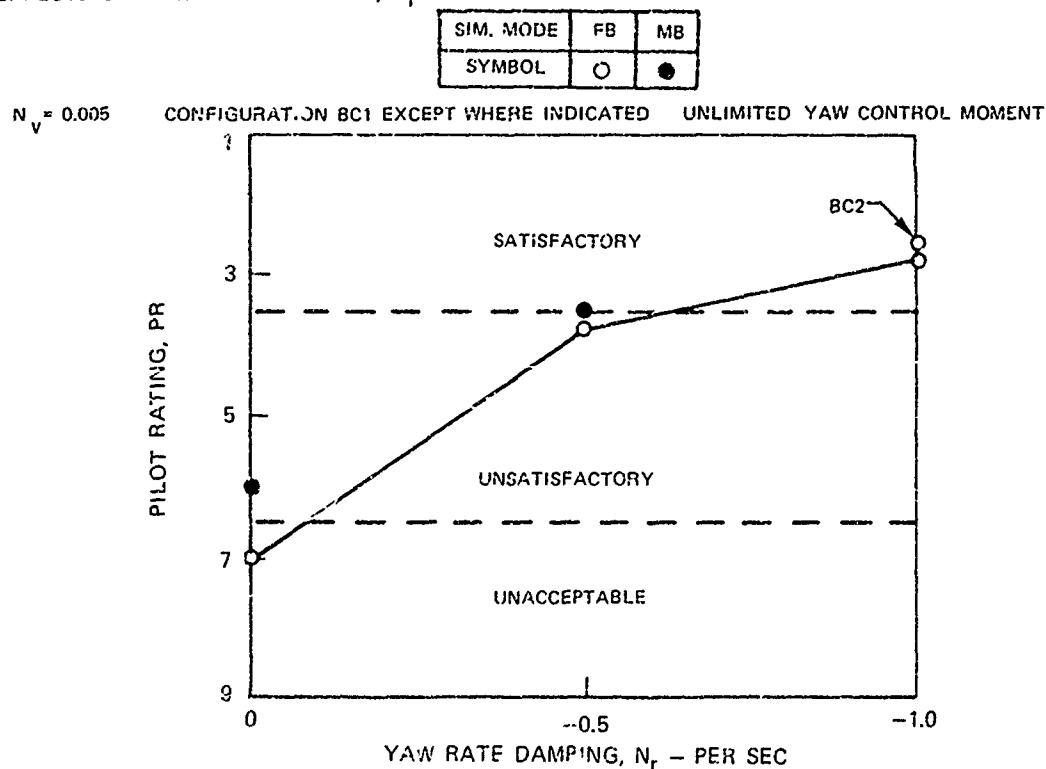


Figure 52. Effect of First-Order Thrust Lags on Incremental Thrust 5-Percent Exceedance Levels Computed for Increased Thrust Commands

(a) EFFECTS OF YAW RATE DAMPING, N_r



(b) COMBINED EFFECTS OF YAW LAGS, τ_ψ , AND DELAYS, d_ψ , AND N_r

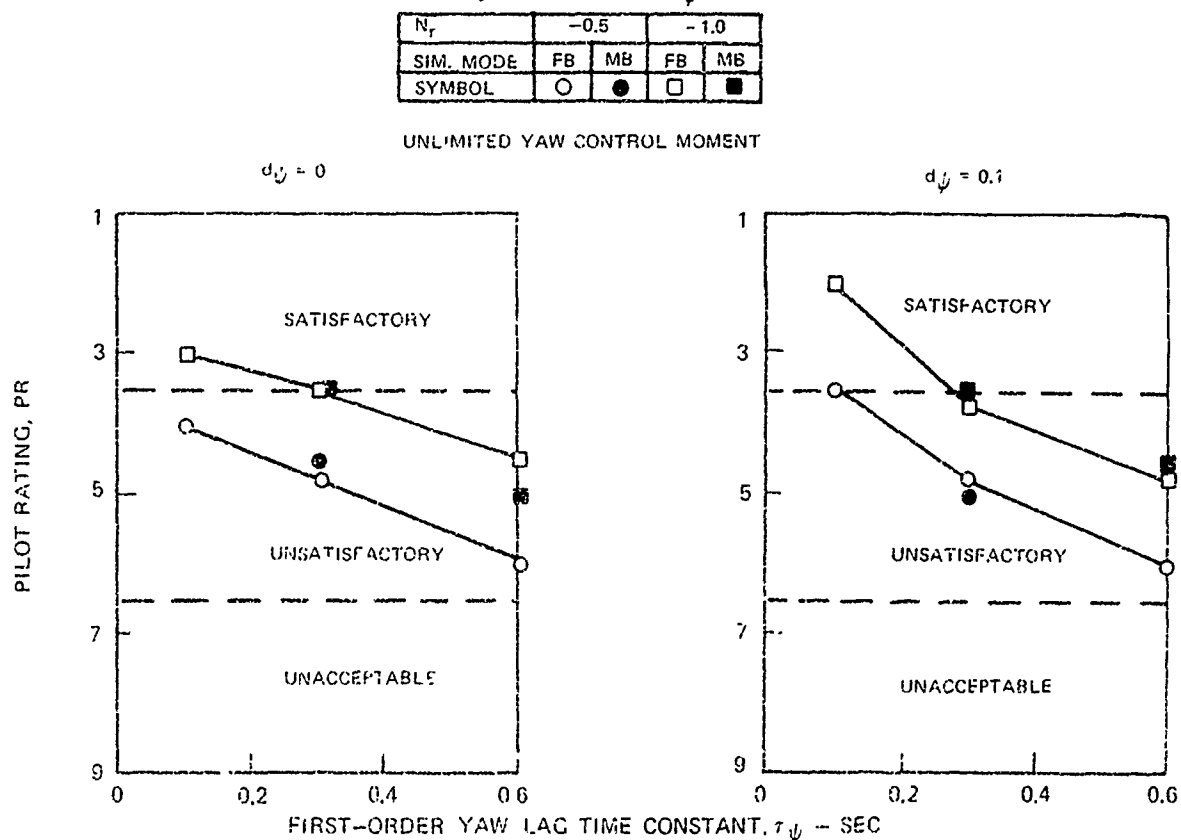


Figure 53. Pilot Rating Results Showing the Effects of Yaw Rate Damping and Lags and Delays in Yaw Control Response

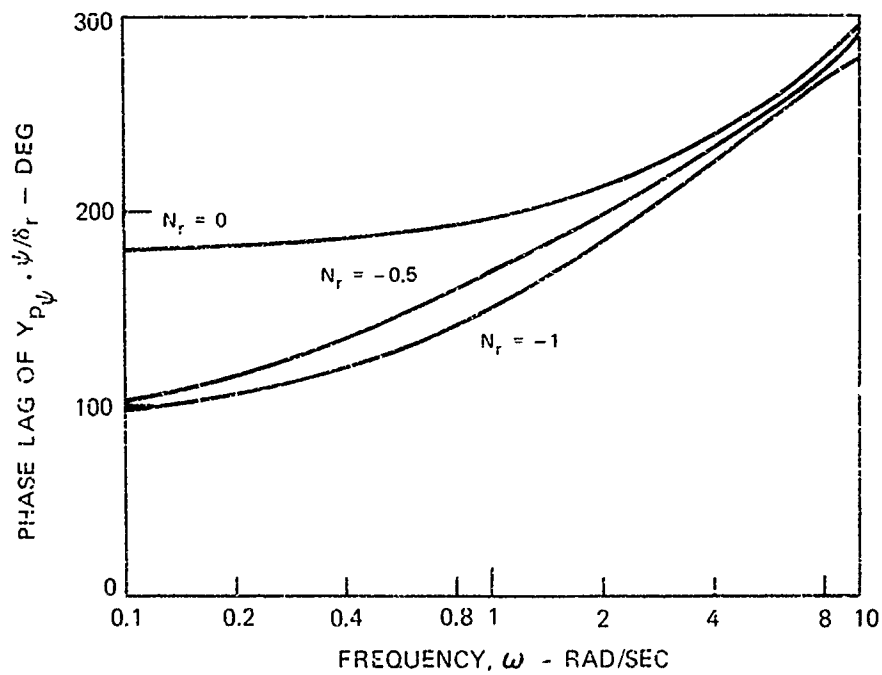


Figure 54. Phase Lag for Pilot-Yaw Open-Loop Dynamics at Several Levels of N_r

| N_r | -0.5 | | -1.0 | |
|-----------|------|----|------|----|
| SIM. MODE | FB | MB | FB | MB |
| SYMBOL | ○ | ● | □ | ■ |

CONFIGURATION BC1

$\bar{N}_{c5} = 0.10 \text{ RAD/SEC}^2 = \text{YAW CONTROL MOMENT 5-PERCENT EXCEEDANCE LEVEL WITH UNLIMITED MOMENT AVAILABLE}$

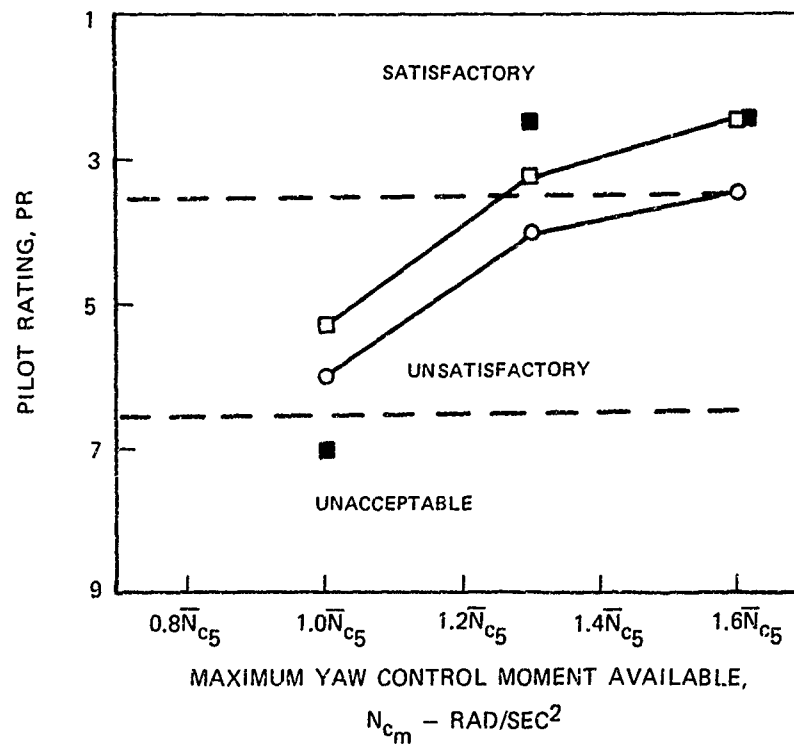


Figure 55. Effects of Yaw Control-Moment Limits on Pilot Rating

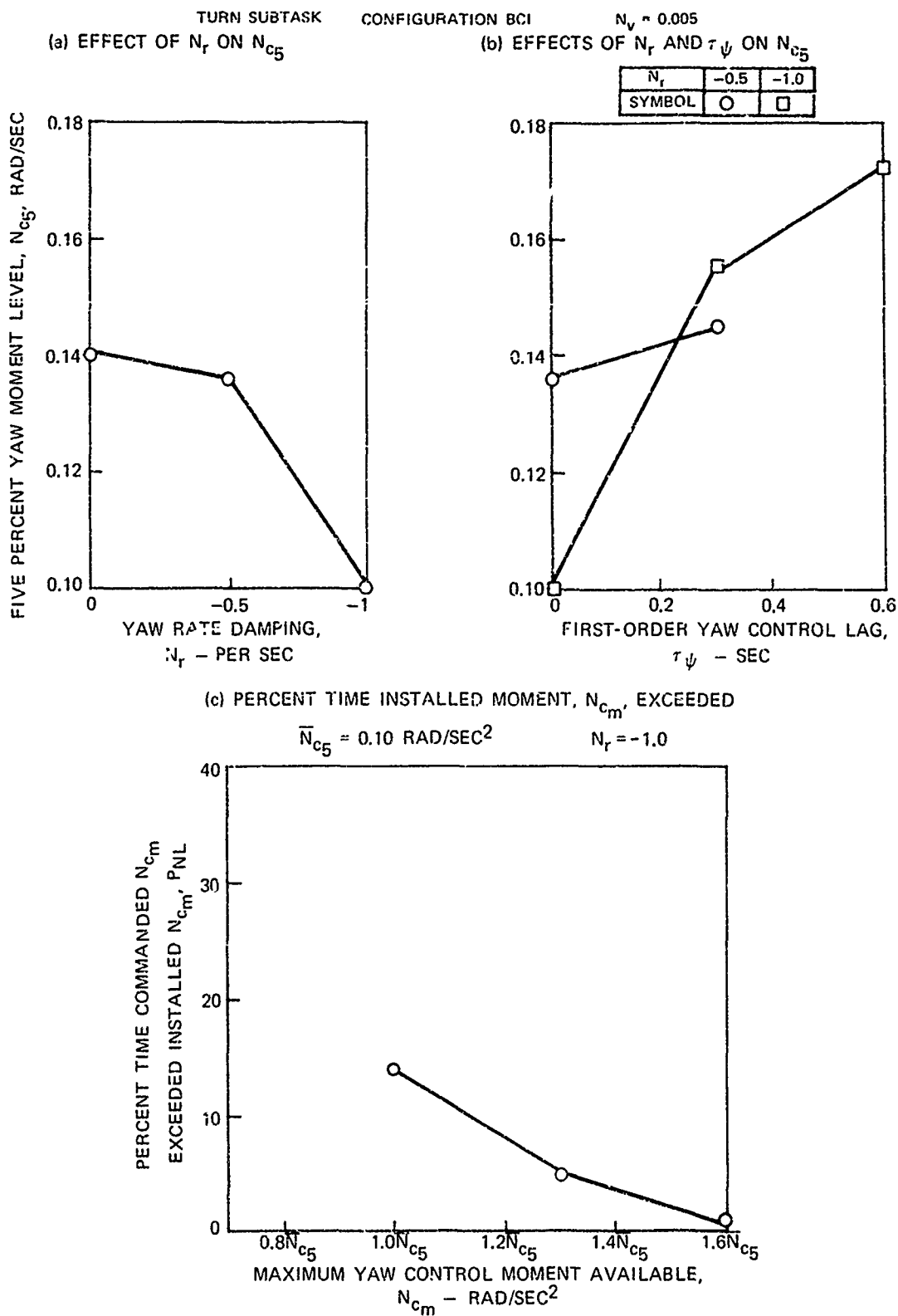


Figure 56. Yaw Control-Moment-Usage Results

APPENDIX A

SUMMARY OF FLYING QUALITIES DATA FROM UARL PILOT EVALUATIONS

This Appendix contains a detailed tabulation of the flying qualities data (pilot ratings and pilot-selected control sensitivities) obtained from the flight simulator evaluations with UARL pilots.

Table A-I identifies the studies conducted in the UARL program and lists the parameters for the cases evaluated in each investigation. It also provides a key to the tables which summarize data in Appendices A, B and C. Tables A-II through A-VIII list results from the longitudinal and lateral control studies in the following sequence: A-II, turbulence effects; A-III, control lags and delays; A-IV, control moment limits; A-V, control moments through stored energy; A-VI, inter-axis motion coupling; A-VII, independent thrust-vector control; and A-VIII, rate-command/attitude-hold control. Flying qualities results from the height control studies are listed in Tables A-IX and A-X as follows: A-IX, velocity damping and thrust-to-weight ratio interactive effects; and A-X, thrust lags and delays and incremental thrust through stored energy. Finally, pilot ratings and pilot-selected sensitivities from the directional control studies are summarized in Table A-XI.

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TABLE A-1

SUMMARY OF PARAMETERS FOR CASES EVALUATED AND
KEY TO TABLES SUMMARIZING DATA

P: Indicates Parameter Varied During Study F: Control Sensitivity Fixed

S: Control Sensitivity Selected by Pilot UL: Unlimited

| Study | Parameters | Cases | Basic Conf. | Longitudinal ¹ | | | | | | Vertical | | | Directional | | | | Pilot Qualities Results Table No. | Pilot Comments Table No. | Control Moment or T/W Usage Table No. | | | |
|---|--|----------|--------------------------|---------------------------|-------|------|------|------|-----------------|----------|-----|-----|-------------|------|-------|-------|-----------------------------------|--------------------------|---------------------------------------|--------|---|-------------------------------------|
| | | | | Mδ | Yδ | Xδ | Mδ | Mδ | σ _{Mδ} | Zδ | T/W | Zδ | Yδ | Nδ | Nδ | | | | | | | |
| Effects of Turbulence | σ _{Mδ} = σ _{Yδ} ² | T1-T15 | RC1 | 0.33 | -0.05 | -1.7 | -1.7 | -1.7 | UL | S | P | -1 | 1.15 | -3.2 | 0.000 | -1 | UL | 0.20 | A-II | B-I | C-I | |
| | | | RC2 | 1.0 | -0.05 | -1.1 | -1.1 | -1.1 | | | | | | | | | | | | | | |
| | | | RC3 | 1.0 | -0.05 | -2.0 | -2.0 | -2.0 | | | | | | | | | | | | | | |
| | | | RC4 | 1.0 | -0.05 | -1.0 | -1.0 | -1.0 | | | | | | | | | | | | | | |
| | | | RC5 | 1.0 | -0.05 | -1.1 | -1.1 | -1.1 | | | | | | | | | | | | | | |
| Lags and delays in pitch and roll control | τ _p = τ _r δ _p = δ _r δ̇ _p = δ̇ _r δ̇ _{ref} = δ̇ _{max} | L11-L127 | RC1 through RC6 | Same as T1-T15 | | | | | | UL | S | 3.4 | -1 | 1.15 | -3.2 | 0.000 | -1 | UL | 0.20 | A-III | B-II | C-II |
| Pitch, roll and yaw moment limits | M _δ , L _δ , N _δ τ _p = τ _r δ̇ _p = δ̇ _r | L11-L125 | RC1 RC4 RC5 RC6 | Same as T1-T15 | | | | | | P | S | 3.4 | -1 | 1.15 | -3.2 | 0.000 | -1 | F | 0.20 | A-IV | B-III | C-III |
| Pitch control moment through stored energy | M _δ , L _δ , N _δ τ _p | L11-L113 | RC1 RC4 RC5 RC6 | Same as T1-T15 | | | | | | P | S | 3.4 | -1 | 1.15 | -3.2 | 0.000 | -1 | UL | 0.20 | A-V | B-IV | C-IV control moment not measured |
| Inter-axis motion coupling | M _δ , L _δ , N _δ τ _p , τ _r δ̇ _p , δ̇ _r | L11-L105 | RC1 | Same as T1-T15 | | | | | | UL | S | 3.4 | -1 | 1.15 | -3.2 | 0.000 | -1 | UL | 0.20 | A-VI | B-V | C-V |
| Independent longitudinal thrust-vector control | δ̇ _{ref} , δ̇ _{max} δ̇ _{max} | L11-L115 | RC1 RC2 RC4 | Same as T1-T15 | | | | | | UL | S | 3.4 | -1 | 1.15 | -3.2 | 0.000 | -1 | UL | 0.20 | A-VII | B-I | C-V |
| Rate command/attitude hold control | M _δ , L _δ , N _δ , τ _p , τ _r δ̇ _{ref} , δ̇ _{max} | L11-L115 | RC1 | 0.33 | -0.05 | P | P | P | UL | S | 3.4 | -1 | 1.15 | -3.2 | 0.000 | -1 | UL | 0.20 | A-VIII | B-VI | C-VI | |
| | | | RC4 | 1.0 | -0.20 | P | P | P | | | | | | | | | | | | | | |
| Velocity damping and thrust-to-weight ratio effects on height control | Z _δ , δ̇ _{ref} , δ̇ _{max} δ̇ _{ref} , δ̇ _{max} | L11-L125 | RC1 | 0.33 | -0.05 | -1.7 | -1.7 | -1.7 | UL | P | 3.4 | P | F | S | 0.000 | -1 | UL | 0.20 | A-IX | B-VIII | C-VII | |
| | | | RC4 | 1.0 | -0.20 | -3.0 | -3.0 | -3.0 | | | | | | | | | | | | | | |
| Lags and delays in thrust response | τ _h = τ _r | L11-L125 | RC1 | 0.33 | -0.05 | -1.7 | -1.7 | -1.7 | UL | P | 3.4 | P | 1.05 | S | 0.000 | -1 | UL | 0.20 | A-X | B-IX | C-VII | |
| Incremental thrust through stored energy | δ̇ _{ref} , δ̇ _{max} | L11-L125 | RC1 | 0.33 | -0.05 | -1.7 | -1.7 | -1.7 | UL | P | 3.4 | P | F | S | 0.000 | -1 | UL | 0.20 | A-X | B-IX | C-VII thrust usage data not measured | |
| Directional control studies | τ _p , τ _r , δ̇ _{ref} δ̇ _{ref} , δ̇ _{max} | D1-D12 | RC1 | 0.33 | -0.05 | -1.7 | -1.7 | -1.7 | UL | P | 3.4 | -1 | 1.15 | -3.2 | 0.000 | P | P | S | A-XI | B-X | C-VIII | |
| | | | RC2 | 1.0 | -0.05 | -1.1 | -1.1 | -1.1 | | | | | | | | | | | | | | |

1. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

Also, if a longitudinal term is treated as a parameter, the corresponding lateral term is as well.

2. Longitudinal and lateral turbulence levels always equal throughout this program.

3. Pitch and roll control lags always equal. Pitch and roll control delays also always equal.

4. Wind simulation included a mean wind from the north, $U_0 = 10$ kts.5. Maximum roll moment, $L_{\dot{\delta}}$, unlimited.

TABLE A-II

FLYING QUALITIES RESULTS FROM THE STUDY OF THE EFFECTS OF TURBULENCE INTENSITY

Vertical and Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-I

| Case | Basic Conf. | Stability Derivatives ¹ | | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | σ_{ϕ}^2 | σ_{ψ}^2 | Pilot | Fixed Base | | | Moving Base | | |
|----------------|-------------|------------------------------------|-------------|-------------|------------------|-----------|---|-------------------|-------------------|------------------|----------------------------------|----------------------------------|--------------------------|---------------------|---------------------|------------|
| | | $\dot{m}_{\dot{u}}$ | \dot{x}_u | \dot{m}_q | \dot{m}_θ | | | | | | $\dot{M}_{\dot{u}}$ | $\dot{L}_{\dot{u}}$ | PR | $\dot{M}_{\dot{u}}$ | $\dot{L}_{\dot{u}}$ | PR |
| T1 " " " " | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | $-0.81 \pm j1.85$ | 3.4 " " " " | 3.4 " " " " | A B B B | 0.330 0.206 0.268 0.412 | 0.308 0.304 0.239 0.398 | 2.0 2.0 2.0 4.5 | 0.313 | 0.248 | 2.0 |
| T4 " " " " | BC5 | 0.33 | -0.20 | -1.7 | -4.2 | -0.29 | $-0.81 \pm j1.85$ | 3.4 " " " " | 3.4 " " " " | A B B B | 0.307 0.306 0.358 0.307 | 0.205 0.248 0.248 0.365 | 4.0 3.0 3.0 4.5 | 0.289 | 0.221 | 3.0 |
| T7 " " " " | BC4 | 1.0 | -0.20 | -3.0 | -1.7 | -2.5 | $-0.35 \pm j0.64$ | 3.4 " " " " | 3.4 " " " " | A B B B | 0.333 0.274 0.452 0.616 | 0.331 0.225 0.380 0.388 | 3.0 4.0 3.0 8.0 | 0.380 | 0.301 | 3.0 |
| T10 " " " " | BC2 | 1.0 | -0.05 | -1.1 | -2.5 | -0.5 | $-0.30 \pm j1.47$ | 3.4 " " " " | 3.4 " " " " | A B B B | 0.373 0.343 0.416 0.445 | 0.320 0.350 0.340 0.342 | 4.0 5.0 6.0 8.0 | 0.375 | 0.297 | 3.0 |
| T13 " " " " | BC6 | 1.0 | -0.20 | -1.1 | -2.5 | -0.65 | $-0.32 \pm j1.48$ | 3.4 " " " " | 3.4 " " " " | A B B B | 0.342 0.298 0.452 0.581 | 0.285 0.242 0.363 0.352 | 4.5 5.0 7.0 9.0 | 0.320 0.136 | 0.260 0.390 | 6.0 7.0 |
| T16 " " " " | BC3 | 1.0 | -0.05 | -2.0 | 0 | -2.2 | $0.08 \pm j0.68$ | 3.4 " " " " | 3.4 " " " " | A B B B | 0.359 0.449 0.439 0.467 | 0.427 0.419 0.373 0.352 | 5.0 3.0 6.0 8.0 | 0.407 | 0.280 | 6.0 |

1. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

2. Mean wind, $U_m = 10$ kts.

TABLE A-III

LONGITUDINAL AND LATERAL FLYING QUALITIES RESULTS FROM THE STUDY OF CONTROL SYSTEM LAGS AND DELAYS

Vertical and Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-II

| Case ¹ | Basic Conf. | Stability For variations | | | Real Root | Complex Roots $-\lambda_1 \pm j\lambda_2$ | First-order Control Lags | | | Second-order Control Lags | | | Cont. dl Delays | | Lateral | | | Lateral Base | | | Moving Base | |
|-------------------|-------------|--------------------------|-----------|----------|---------------|---|--------------------------|----------|----------|---------------------------|----------|----------|-----------------|----------|----------|----------|----------|--------------|----------|----------|-------------|----------|
| | | η_{ue} | ζ_e | η_g | η_θ | | τ_e | τ_a | τ_b | τ_c | τ_d | τ_e | τ_f | τ_g | τ_h | τ_i | τ_j | τ_k | τ_l | τ_m | τ_n | τ_o |
| LL1 | BC1 | 0.33 | -0.05 | -1.7 | -1.2 | -0.13 | 0.1 | 0.1 | - | - | - | - | - | - | 0.203 | 0.248 | 0.2 | 0.203 | 0.248 | 0.2 | 0.203 | 0.248 |
| LL2 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.291 | 0.267 | 3.0 | 0.291 | 0.267 | 3.0 | 0.291 | 0.267 |
| LL3 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.330 | 0.251 | 2.5 | 0.330 | 0.251 | 2.5 | 0.330 | 0.251 |
| LL4 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.355 | 0.358 | 2.0 | 0.355 | 0.358 | 2.0 | 0.355 | 0.358 |
| LL5 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.339 | 0.269 | 3.0 | 0.339 | 0.269 | 3.0 | 0.339 | 0.269 |
| LL6 | BC5 | 0.33 | -0.05 | -1.7 | -1.2 | -0.29 | 0.1 | 0.1 | - | - | - | - | - | - | 0.302 | 0.242 | 2.0 | 0.302 | 0.242 | 2.0 | 0.302 | 0.242 |
| LL7 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.296 | 0.254 | 2.0 | 0.296 | 0.254 | 2.0 | 0.296 | 0.254 |
| LL8 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.241 | 0.312 | 3.0 | 0.241 | 0.312 | 3.0 | 0.241 | 0.312 |
| LL9 | BC4 | 1.0 | -0.20 | -3.0 | -1.7 | -2.5 | 0.1 | 0.1 | - | - | - | - | - | - | 0.424 | 0.319 | 2.0 | 0.424 | 0.319 | 2.0 | 0.424 | 0.319 |
| LL10 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.359 | 0.369 | 2.5 | 0.359 | 0.369 | 2.5 | 0.359 | 0.369 |
| LL11 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.315 | 0.275 | 3.0 | 0.315 | 0.275 | 3.0 | 0.315 | 0.275 |
| LL12 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.437 | 0.338 | 4.0 | 0.437 | 0.338 | 4.0 | 0.437 | 0.338 |
| LL13 | BC6 | 2.0 | -0.20 | -2.1 | -2.5 | -0.65 | 0.1 | 0.1 | - | - | - | - | - | - | 0.461 | 0.404 | 2.0 | 0.461 | 0.404 | 2.0 | 0.461 | 0.404 |
| LL14 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.409 | 0.280 | 4.0 | 0.409 | 0.280 | 4.0 | 0.409 | 0.280 |
| LL15 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.344 | 0.277 | 5.0 | 0.344 | 0.277 | 5.0 | 0.344 | 0.277 |
| LL16 | BC3 | 1.0 | -0.05 | -2.0 | 0 | -2.2 | 0.6 | 0.6 | " | " | " | " | " | " | 0.387 | 0.303 | 8.0 | 0.387 | 0.303 | 8.0 | 0.387 | 0.303 |
| LL17 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.414 | 0.374 | 9.0 | 0.414 | 0.374 | 9.0 | 0.414 | 0.374 |
| LL18 | " | " | " | " | " | " | 0.6 | 0.6 | " | " | " | " | " | " | 0.432 | 0.348 | 4.0 | 0.432 | 0.348 | 4.0 | 0.432 | 0.348 |
| LL19 | BC1 | 0.33 | -0.05 | -1.7 | -1.2 | -0.15 | - | - | - | - | - | - | - | - | 0.314 | 0.193 | 4.5 | 0.314 | 0.193 | 4.5 | 0.314 | 0.193 |
| LL20 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.303 | 0.257 | 5.0 | 0.303 | 0.257 | 5.0 | 0.303 | 0.257 |
| LL21 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.434 | 0.350 | 6.0 | 0.434 | 0.350 | 6.0 | 0.434 | 0.350 |
| LL22 | BC2 | 1.0 | -0.05 | -2.0 | 0 | -2.2 | 0.1 | 0.1 | - | - | - | - | - | - | 0.427 | 0.371 | 6.0 | 0.427 | 0.371 | 6.0 | 0.427 | 0.371 |
| LL23 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.436 | 0.455 | 2.0 | 0.436 | 0.455 | 2.0 | 0.436 | 0.455 |
| LL24 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.452 | 0.365 | 7.0 | 0.452 | 0.365 | 7.0 | 0.452 | 0.365 |
| LL25 | " | " | " | " | " | " | 0.6 | 0.6 | " | " | " | " | " | " | 0.595 | 0.602 | 10.0 | 0.595 | 0.602 | 10.0 | 0.595 | 0.602 |
| LL26 | BC1 | 0.33 | -0.05 | -1.7 | -1.2 | -0.13 | 0 | 0 | - | - | - | - | - | - | 0.422 | 0.369 | 7.0 | 0.422 | 0.369 | 7.0 | 0.422 | 0.369 |
| LL27 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.295 | 0.284 | 7.0 | 0.295 | 0.284 | 7.0 | 0.295 | 0.284 |
| LL28 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.300 | 0.272 | 10.0 | 0.300 | 0.272 | 10.0 | 0.300 | 0.272 |
| LL29 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.352 | 0.310 | 4.0 | 0.352 | 0.310 | 4.0 | 0.352 | 0.310 |
| LL30 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | 0.317 | 0.257 | 3.0 | 0.317 | 0.257 | 3.0 | 0.317 | 0.257 |
| LL31 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.297 | 0.200 | 4.0 | 0.297 | 0.200 | 4.0 | 0.297 | 0.200 |
| LL32 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.357 | 0.264 | 3.0 | 0.357 | 0.264 | 3.0 | 0.357 | 0.264 |
| LL33 | " | " | " | " | " | " | 0.3 | 0.3 | " | " | " | " | " | " | 0.332 | 0.270 | 5.0 | 0.332 | 0.270 | 5.0 | 0.332 | 0.270 |
| LL34 | " | " | " | " | " | " | 0 | 0 | - | - | - | - | - | - | 0.399 | 0.334 | 5.0 | 0.399 | 0.334 | 5.0 | 0.399 | 0.334 |
| LL35 | " | " | " | " | " | " | 0.2 | 0.2 | - | - | - | - | - | - | 0.363 | 0.334 | 7.0 | 0.363 | 0.334 | 7.0 | 0.363 | 0.334 |

- Standard wind simulation; $\sigma_{ug} = \sigma_{vg} = 3.4$ ft/sec, $U_{\infty} = 10$ kts.
- Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
- Lag and delay affect both the control and stability augmentation system inputs.

TABLE A-IV

FLYING QUALITIES RESULTS FROM THE STUDY OF PITCH, ROLL AND YAW CONTROL MOMENT LIMITS

Vertical and Directional Parameters listed in Table A-I
Pilot Comments Given in Table B-III

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Maximum Control Moments Available | | | | First-Order Control Lag ² | | | Control Delay | | Pilot | Fixed Base | | | Moving Base | | |
|-------------------|-------------|------------------------------------|----------------|----------------|----------------|-----------|---|-----------------------------------|----------------|----------------|----------------|--------------------------------------|----------------|----------------|----------------|----------------|-------|----------------|----------------|------|----------------|----------------|-----|
| | | MUS | Y _r | N _z | N _θ | | | M _z | L _z | N _z | Y _c | τ _z | τ _z | τ _z | d _z | d _z | | W _z | L _z | IF | W _z | L _z | IF |
| IM1 | BC1 | 0.33 | -0.05 | -1.7 | -1.2 | -0.13 | -0.81±j1.85 | 0.360 | 0.415 | 0.120 | - | - | - | - | - | - | B | 0.301 | 0.276 | 7.0 | 0.301 | 0.234 | 7.0 |
| IM2 | " | " | " | " | " | " | " | 0.396 | 0.397 | 0.132 | " | " | " | " | " | " | B | 0.307 | 0.263 | 3.0 | 0.317 | 0.256 | 3.0 |
| IM3 | " | " | " | " | " | " | " | 0.432 | 0.448 | 0.144 | " | " | " | " | " | " | A | 0.296 | 0.243 | 2.0 | " | " | " |
| IM4 | " | " | " | " | " | " | " | " | " | " | " | " | " | " | " | " | A | 0.240 | 0.200 | 2.0 | " | " | " |
| IM5 | " | " | " | " | " | " | " | 0.555 | 0.445 | 0.120 | " | " | " | " | " | " | B | 0.327 | 0.278 | 3.0 | 0.303 | 0.218 | 2.5 |
| IM6 | " | " | " | " | " | " | " | 0.300 | 0.290 | 0.120 | " | " | " | " | " | " | B | 0.337 | 0.269 | 3.0 | " | " | " |
| IM7 | BC5 | 0.33 | -0.20 | -1.7 | -1.2 | -0.29 | -0.81±j1.85 | 0.360 | 0.360 | 0.150 | - | - | - | - | - | - | B | 0.350 | 0.359 | 3.0 | 0.390 | 0.298 | 7.0 |
| IM8 | " | " | " | " | " | " | " | 0.469 | 0.440 | 0.182 | " | " | " | " | " | " | B | 0.270 | 0.233 | 3.0 | 0.297 | 0.218 | 2.5 |
| IM9 | " | " | " | " | " | " | " | 0.820 | 0.605 | 0.175 | " | " | " | " | " | " | A | 0.260 | 0.154 | 6.0 | " | " | " |
| IM10 | " | " | " | " | " | " | " | 0.902 | 0.666 | 0.193 | " | " | " | " | " | " | B | 0.413 | 0.393 | 9.0 | " | " | " |
| IM11 | " | " | " | " | " | " | " | 0.984 | 0.727 | 0.211 | " | " | " | " | " | " | A | 0.215 | 0.204 | 8.0 | " | " | " |
| IM12 | BC6 | 1.0 | -0.20 | -1.1 | -2.5 | -0.65 | -0.35±j0.64 | 1.066 | 0.785 | 0.229 | - | - | - | - | - | - | S | 0.432 | 0.404 | 4.5 | 0.426 | 0.348 | 5.0 |
| IM13 | " | " | " | " | " | " | " | 0.890 | 0.750 | 0.170 | " | " | " | " | " | " | B | 0.304 | 0.304 | 4.5 | 0.428 | 0.334 | 4.5 |
| IM14 | " | " | " | " | " | " | " | 0.979 | 0.895 | 0.197 | " | " | " | " | " | " | B | 0.387 | 0.351 | 7.0 | " | " | " |
| IM15 | " | " | " | " | " | " | " | 1.068 | 0.900 | 0.204 | " | " | " | " | " | " | B | 0.228 | 0.182 | 10.0 | " | " | " |
| IM16 | " | " | " | " | " | " | " | 1.157 | 0.975 | 0.221 | " | " | " | " | " | " | A | 0.367 | 0.353 | 5.0 | 0.393 | 0.325 | 6.0 |
| IM17 | BC1 | 0.33 | -0.05 | -1.7 | -1.2 | -0.13 | -0.81±j1.85 | 0.356 | 0.457 | 0.132 | 0.3 | 0.3 | 0.3 | 0.3 | 0.1 | 0.1 | A | 0.266 | 0.259 | 7.0 | 0.400 | 0.335 | 5.0 |
| IM18 | " | " | " | " | " | " | " | 0.432 | 0.458 | 0.144 | 0.3 | 0.3 | 0.3 | 0.3 | 0.1 | 0.1 | B | 0.339 | 0.264 | 4.0 | 0.348 | 0.297 | 4.5 |
| IM19 | " | " | " | " | " | " | " | 0.468 | 0.540 | 0.156 | 0.3 | 0.3 | 0.3 | 0.3 | 0.1 | 0.1 | A | 0.339 | 0.264 | 4.0 | 0.306 | 0.245 | 3.0 |
| IM20 | " | " | " | " | " | " | " | 0.364 | 0.457 | 0.132 | 0.6 | 0.6 | 0.6 | 0.6 | 0.1 | 0.1 | B | 0.346 | 0.275 | 2.5 | " | " | " |
| IM21 | " | " | " | " | " | " | " | 0.432 | 0.493 | 0.144 | 0.6 | 0.6 | 0.6 | 0.6 | 0.1 | 0.1 | A | 0.371 | 0.312 | 4.5 | " | " | " |
| IM22 | " | " | " | " | " | " | " | 0.468 | 0.540 | 0.156 | 0.6 | 0.6 | 0.6 | 0.6 | 0.1 | 0.1 | B | 0.384 | 0.325 | 1.0 | " | " | " |
| IM23 | BC5 | 0.33 | -0.20 | -1.7 | -1.2 | -0.29 | -0.81±j1.85 | 0.420 | 0.400 | 0.165 | 0.6 | 0.6 | 0.6 | 0.6 | 0.1 | 0.1 | B | 0.366 | 0.257 | 3.0 | " | " | " |
| IM24 | " | " | " | " | " | " | " | 0.462 | 0.440 | 0.182 | 0.6 | 0.6 | 0.6 | 0.6 | 0.1 | 0.1 | A | 0.268 | 0.312 | 1.0 | " | " | " |
| IM25 | " | " | " | " | " | " | " | 0.504 | 0.450 | 0.199 | 0.6 | 0.6 | 0.6 | 0.6 | 0.1 | 0.1 | B | 0.338 | 0.323 | 3.5 | " | " | " |

1. Standard wind simulation. $\sigma_{u_g} = \sigma_{v_r} = 3.4$ ft/sec, $u_0 = 10$ kts.

2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

TABLE A-V

LONGITUDINAL FLYING QUALITIES RESULTS FROM THE STUDY OF INCREMENTAL CONTROL MOMENTS THROUGH STORED ENERGY

Vertical and Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-IV

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Control-Moment, Stored Energy Parameters ³ | | | | Pilot | Fixed Base | | | Moving Base | | | |
|-------------------|-------------|------------------------------------|----------------|----------------|----------------|-----------|---|---|-----------------|----------------|-----------------|-------|-----------------|-------|-----------------|-----------------|------|------|-----|
| | | M _δ | χ _u | M _η | M _θ | | | M _{Cm} | ΔM _C | γ _A | M _{δc} | | L _{δu} | PR | M _{δc} | L _{δu} | PR | | |
| LS1 | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | -0.81±j1.85 | 0.356 | 30% | 0.05 | B | | 0.320 | 0.251 | 3.0 | .254 | .192 | 5.5 | |
| LS2 | | " | | | | | | 0.356 | 30% | 0.10 | A | | 0.300 | 0.224 | 5.0 | | | | |
| LS3 | | " | | | | | | | 0.356 | 30% | 0.20 | E | | 0.303 | 0.253 | 4.5 | .254 | .192 | 4.0 |
| LS4 | | " | | | | | | | 0.356 | 50% | 0.20 | B | | 0.297 | 0.251 | 2.0 | | | |
| LS5 | BC5 | 0.33 | -0.20 | -1.7 | -4.2 | -0.29 | -0.81±j1.85 | 0.300 | 30% | 0.10 | B | | 0.310 | 0.255 | 7.0 | | | | |
| LS6 | | " | | | | | | 0.340 | 30% | 0.05 | B | | 0.314 | 0.265 | 6.0 | | | | |
| LS7 | | " | | | | | | | 0.340 | 30% | 0.20 | A | | 0.347 | 0.247 | 4.5 | | | |
| " | | | | | | | | | " | " | " | B | | 0.303 | 0.258 | 4.0 | | | |
| LS8 | BC4 | 1.0 | -0.20 | -3.0 | -1.7 | -2.5 | -0.35±j0.64 | 0.902 | 0 | 0 | B | | | | | .371 | .333 | 5.5 | |
| LS9 | | " | | | | | | 0.902 | 30% | 0.05 | B | | 0.373 | 0.310 | 8.0 | .361 | .342 | 5.0 | |
| LS10 | | " | | | | | | | 0.902 | 30% | 0.10 | A | | 0.401 | 0.333 | 5.0 | | | |
| " | | | | | | | | | | " | " | B | | 0.291 | 0.241 | 7.0 | | | |
| LS11 | BC6 | | | | | | | 0.902 | 30% | 0.20 | A | | 0.381 | 0.294 | 8.0 | .382 | .337 | 4.0 | |
| " | | | | | | | | " | " | " | B | | | | | | | | |
| LS12 | | " | 1.0 | -0.20 | -1.1 | -2.5 | -0.65 | -0.32±j1.48 | 0.979 | 30% | 0.10 | A | | 0.246 | 0.138 | 9.0 | | | |
| " | | | | | | | | | " | " | " | B | | 0.388 | 0.340 | 6.0 | | | |
| LS13 | | | | | | | | 0.979 | 30% | 0.20 | A | | 0.254 | 0.134 | 8.0 | | | | |
| LS14 | | | | | | | | | 0.979 | 30% | 0.20 | B | | 0.410 | 0.299 | 5.0 | | | |

1. Standard wind simulation; $\sigma_{\dot{\alpha}} = \sigma_{\dot{\eta}} = 3.4$ ft/sec, $U_0 = 10$ kts.
2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Stored energy effects were only simulated in the pitch axis. Roll and yaw control moments were unlimited.

TABLE A-VI

LONGITUDINAL AND LATERAL FLYING QUALITIES RESULTS FROM THE STUDY OF RATE-COMMAND/ATTITUDE-HOLD CONTROL

Vertical and Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-VII

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | | Real Root | Complex Roots $-4\alpha_1 \pm i4\beta_1$ | Damping Ratio and Natural Frequency | | Pilot | Fixed Base | | | Moving Base | | |
|-------------------|-------------|------------------------------------|-------|-------|-------|-----------|---|-------------------------------------|------------|-------|----------------|----------------|-------|----------------|----------------|-------|
| | | $M_{u\delta}$ | X_u | Y_q | M_q | | | ζ | ω_n | | $M_{\delta c}$ | $L_{\delta n}$ | T_R | $M_{\delta c}$ | $L_{\delta n}$ | T_R |
| LR1 | BC1 | 0.33 | -0.05 | -2 | -8 | -0.092 | -0.98 ± i2.64 | 0.35 | 5.8 | B | 0.812 | 0.116 | 1.5 | 3.134 | 3.498 | 4.5 |
| LR2 | | | | -2 | -40 | -0.058 | -1.00 ± i6.24 | 0.16 | 6.3 | B | 2.408 | 0.110 | 1.5 | | | |
| LR3 | | | | -4 | -8 | -0.093 | -1.98 ± i1.98 | 0.71 | 2.8 | A | 0.004 | 0.004 | 5.0 | | | |
| " | | | | " | " | " | " | " | " | B | 0.981 | 0.884 | 5.0 | | | |
| LR4 | | | | -4 | -40 | -0.058 | -2.00 ± i6.00 | 0.32 | 6.3 | B | 3.600 | 3.340 | 2.0 | | | |
| LR5 | | | | -6 | -12 | -0.079 | -2.99 ± i1.71 | 0.87 | 3.44 | B | 1.792 | 1.528 | 4.0 | | | |
| LR6 | | | | -6 | -40 | -0.058 | -3.00 ± i5.57 | 0.47 | 6.32 | B | 2.588 | 2.208 | 2.5 | 4.182 | 4.698 | 3.5 |
| LR7 | | | | -8 | -40 | -0.058 | -4.20 ± i4.90 | 0.63 | 6.32 | A | 3.044 | 2.420 | 4.0 | | | |
| LR8 | | | | -10 | -50 | -0.055 | -5.00 ± i5.50 | 0.67 | 7.43 | A | 3.960 | 3.314 | 3.0 | 5.532 | 6.300 | 3.0 |
| " | | | | " | " | " | " | " | " | B | | | | | | |
| LR9 | BC4 | 1.0 | -0.20 | -2 | -16 | -0.28 | -0.99 ± i3.87 | 0.248 | 4.0 | B | 1.192 | 0.864 | 4.5 | | | |
| LR10 | | | | -2 | -25 | -0.26 | -0.99 ± i5.32 | 0.200 | 5.0 | B | 2.152 | 1.868 | 5.0 | | | |
| LR11 | | | | -4 | -16 | -0.27 | -1.97 ± i3.45 | 0.500 | 4.0 | B | 1.648 | 1.396 | 3.5 | 2.178 | 2.274 | 5.0 |
| LR12 | | | | -4 | -25 | -0.24 | -1.97 ± i4.54 | 0.400 | 5.0 | B | 2.584 | 2.284 | 3.0 | | | |
| LR13 | | | | -6 | -16 | -0.27 | -2.97 ± i2.61 | 0.750 | 4.0 | B | 1.632 | 1.372 | 3.0 | | | |
| LR14 | | | | -6 | -26 | -0.25 | -2.98 ± i4.06 | 0.610 | 5.0 | B | 2.208 | 1.912 | 3.0 | 3.756 | 3.732 | 4.5 |
| LR15 | | | | -10 | -50 | -0.22 | -4.99 ± i5.51 | 0.670 | 7.43 | A | 3.756 | 3.228 | 3.0 | 5.010 | 5.694 | 3.0 |
| " | | | | " | " | " | " | " | " | B | | | | | | |

1. Standard wind simulation; $\sigma_{bg} = 3.4$ ft/sec, $U_m = 10$ kts.

2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

TABLE A-VII

LONGITUDINAL FLYING QUALITIES RESULTS FROM THE STUDY OF INDEPENDENT THRUST-VECTOR CONTROL

Vertical and Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-VI

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Thrust Vector Control Parameters | | | Pilot | Fixed Base | | Moving Base | | | |
|-------------------|-------------|------------------------------------|----------------|----------------|-----------------|-----------|---|----------------------------------|-----------------|-------------------------|-------|-------------------|-----------------|-------------|-----------------|-----------------|-----|
| | | M _{uδ} | X _u | M _q | M _{q̇} | | | γ ³ | γ _{δc} | $\frac{1}{\delta_{TS}}$ | | M _{δc} | L _{δa} | IF | M _{δc} | L _{δa} | IF |
| LI1 | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | -0.81±j1.85 | 5 | - | - | A | 0.329 | 0.286 | 5.5 | 0.314 | 0.242 | 4.5 |
| LI2 | " | | | | | | | 10 | | | B | 0.314 | 0.242 | 4.0 | 0.314 | 0.242 | 4.0 |
| LI3 | " | | | | | | | 20 | | | B | 0.329 | 0.286 | 3.5 | 0.314 | 0.242 | 3.0 |
| LI4 | BC4 | 1.0 | -0.20 | -3.0 | -1.7 | -2.5 | -0.35±j0.64 | 5 | - | - | B | 0.329 | 0.286 | 4.5 | 0.329 | 0.286 | 5.5 |
| LI5 | " | | | | | | | 10 | | | B | 0.329 | 0.286 | 4.5 | | | |
| LI6 | " | | | | | | | 20 | | | A | 0.329 | 0.286 | 5.0 | 0.329 | 0.286 | 4.0 |
| LI7 | BC2 | 1.0 | -0.05 | -1.1 | -2.5 | -0.5 | -0.30±j1.47 | 5 | - | - | B | 0.338 | 0.335 | 5.0 | | | |
| LI8 | " | | | | | | | 10 | | | A | 0.329 | 0.384 | 6.5 | | | |
| LI9 | " | | | | | | | 20 | | | B | 0.314 | 0.242 | 4.5 | 0.338 | 0.335 | 5.5 |
| LI10 ⁵ | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | -0.81±j1.85 | 20 | - | - | B | 0.314 | 0.242 | 4.0 | | | |
| LI11 | " | | | | | | | - | 2 | 1 | B | N.A. ⁶ | 0.242 | 3.5 | | | |
| LI12 | " | | | | | | | - | 5 | 1 | B | " | 0.242 | 3.0 | | | |
| LI13 | " | | | | | | | - | 10 | 1 | B | " | 0.242 | 3.5 | | | |
| LI14 | BC4 | 1.0 | -0.20 | -3.0 | -1.7 | -2.5 | -0.35±j0.64 | - | 5 | 1 | B | N.A. ⁶ | 0.286 | 10.0 | | | |
| LI15 | BC2 | 1.0 | -0.05 | -1.1 | -2.5 | -0.5 | -0.30±j1.47 | - | 5 | 1 | B | N.A. ⁶ | 0.335 | 10.0 | | | |

- Standard gust simulation; $\sigma_{\delta c} = \sigma_{\gamma} = 3.4$ ft/sec, $U_m = 10$ kts.
- Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
- Thrust-vector thumb-switch control, conventional attitude control.
- Thrust-vector control with stick, thumb-switch attitude control.
- Thrust-vector angle displayed on instrument panel only.
- Not applicable - see $\gamma_{\delta c}$ for longitudinal thrust rotation control sensitivity.

TABLE A-VIII

LONGITUDINAL AND LATERAL FLYING QUALITIES RESULTS FROM THE STUDY OF INTER-AXIS MOTION COUPLING

Vertical and Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-V

| Case | Basic Conf. | Stability Derivatives ² | | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Motion Coupling Parameters | | | | Fixed Base | | | Moving Base | | |
|------|-------------|------------------------------------|-------|-------|--------------------|-----------|---|----------------------------|-------|--------------------|--------------------|--------------------|--------------------|-------|--------------------|--------------------|-------|
| | | $X_{u\delta}$ | X_u | N_u | $X_{\dot{\theta}}$ | | | N_p | L_q | $M_{\dot{\theta}}$ | $L_{\dot{\theta}}$ | $M_{\dot{\theta}}$ | $L_{\dot{\theta}}$ | P_R | $M_{\dot{\theta}}$ | $L_{\dot{\theta}}$ | P_R |
| LC1 | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | $-0.8 \pm j1.65$ | ? | -2 | 0 | 0 | 0.305 | 0.342 | 4.0 | 0.349 | 0.291 | 3.5 |
| " | " | | | | | | | 4 | -4 | 0 | 0 | 0.359 | 0.293 | 3.5 | | | |
| LC2 | " | | | | | | | " | " | " | " | 0.366 | 0.323 | 4.5 | | | |
| LC3 | " | | | | | | | 0 | 0 | 0.25 | -0.25 | 0.376 | 0.299 | 3.0 | | | |
| LC4 | " | | | | | | | 0 | 0 | 0.50 | -0.50 | 0.362 | 0.308 | 2.5 | | | |
| LC5 | " | | | | | | | " | " | " | " | 0.342 | 0.283 | 3.5 | 0.264 | 0.321 | 2.5 |
| LC6 | " | | | | | | | 2 | -2 | 0.25 | -0.25 | 0.313 | 0.290 | 4.0 | 0.310 | 0.360 | 4.0 |
| LC7 | " | | | | | | | 4 | -4 | 0.50 | -0.50 | 0.316 | 0.284 | 4.5 | | | |
| LC8 | " | | | | | | | | | | | 0.412 | 0.358 | 7.5 | | | |
| | | 1.0 | -0.05 | -1.1 | -2.5 | -0.5 | $-0.30 \pm j1.47$ | 2 | -2 | 0.25 | -0.25 | 0.442 | 0.373 | 6.5 | | | |
| | | | | | | | | 2 | -2 | -0.25 | 0.25 | 0.446 | 0.359 | 6.5 | | | |

1. Standard wind simulation; $\sigma_{u\delta} = \sigma_{Vg} = 3.4$ ft/sec, $U_m = 10$ kts.

2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

TABLE A-IX

HEIGHT CONTROL FLYING QUALITIES RESULTS FROM THE STUDY OF THE INTERACTION
BETWEEN HEIGHT VELOCITY DAMPING AND THRUST-TO-WEIGHT RATIO

Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-VIII

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Height Damping, Thrust-to-Weight Parameters | | Pilot | Fixed Base | | Moving Base | |
|-------------------|-------------|------------------------------------|-----------|----------------|-----------|---|---|---------------------|-------|---------------------|------|---------------------|-----|
| | | ζ_u | ζ_q | $\dot{\theta}$ | | | ζ_{w_g} | $\zeta_{\dot{w}_g}$ | | $\zeta_{\dot{w}_g}$ | FR | $\zeta_{\dot{w}_g}$ | FR |
| H21 | BC1 | 0.33 | -0.05 | -4.2 | -0.13 | -0.81 ± j1.85 | 0 | 0 | A | 3.45 | 2.0 | 3.03 | 7.0 |
| " | | | | | | | -0.125 | -0.125 | B | 3.34 | 7.0 | | |
| H22 | | | | | | | " | " | " | 2.98 | 4.0 | 2.57 | 4.0 |
| " | | | | | | | " | " | " | 3.12 | 4.5 | | |
| H23 | | | | | | | -0.25 | -0.25 | A | 3.04 | 2.0 | | |
| H24 | | | | | | | -0.40 | -0.40 | A | 3.50 | 2.0 | | |
| H25 | | | | | | | -0.05 | -0.05 | B | | | | |
| H26 | | | | | | | -0.125 | -0.125 | A | | | | |
| H27 | | | | | | | 0 | 0 | A | 3.0 | 7.0 | 3.05 | 7.0 |
| H28 | | | | | | | -0.25 | -0.25 | A | | 8.0 | | |
| H29 | | | | | | | 0 | 0 | A | | 6.0 | 3.0 | 3.0 |
| H210 | | | | | | | -0.25 | -0.25 | B | | 4.0 | | |
| H211 | | | | | | | -0.40 | -0.40 | A | | 5.0 | | |
| " | | | | | | | " | " | A | | 4.0 | | |
| H212 | | | | | | | -0.025 | -0.025 | B | | | 2.98 | 5.0 |
| H213 | | | | | | | -0.05 | -0.05 | B | | | 3.07 | 6.5 |
| H214 | | | | | | | -0.125 | -0.125 | A | | | 3.01 | 6.0 |
| " | | | | | | | " | " | B | | 3.0 | 2.82 | 3.0 |
| H215 | | | | | | | 0 | -0.25 | A | | 6.0 | | |
| H216 | | | | | | | -0.25 | -0.25 | A | | 5.0 | | |
| H217 | | | | | | | -0.25 | -0.25 | A | | 4.0 | | |
| " | | | | | | | " | " | B | | 2.5 | | |
| H218 | | | | | | | -0.40 | -0.40 | A | | 3.5 | 3.06 | 2.5 |
| H219 | | | | | | | -0.05 | -0.05 | A | | | | |
| H220 | | | | | | | -0.125 | -0.125 | A | | | 3.24 | 4.0 |
| " | | | | | | | " | " | B | | 2.5 | | |
| H221 | | | | | | | 0 | -0.25 | A | | 2.5 | 2.62 | 3.0 |
| " | | | | | | | " | " | B | | 4.5 | | |
| H222 | | | | | | | -0.25 | -0.25 | A | | 5.0 | | |
| " | | | | | | | " | " | B | | 4.0 | | |
| H223 | | | | | | | -0.25 | -0.25 | A | | 2.5 | 2.82 | 3.5 |
| " | | | | | | | " | " | B | | 4.0 | | |
| H224 | | | | | | | -0.40 | -0.40 | A | | 2.5 | 2.76 | 3.5 |
| " | | | | | | | " | " | B | | 2.5 | | |
| H225 | BC4 | 1.0 | -0.20 | -1.7 | -2.5 | -0.35 ± j0.64 | 0 | 0 | A | 3.0 | 10.0 | 3.06 | 8.0 |
| " | | | | | | | " | " | B | 3.0 | 8.0 | | |
| H226 | | | | | | | -0.125 | -0.125 | A | 2.60 | 5.0 | 2.70 | 4.5 |
| " | | | | | | | " | " | B | 3.28 | 4.5 | | |
| H227 | | | | | | | -0.25 | -0.25 | A | 3.71 | 3.0 | | |
| H228 | | | | | | | -0.40 | -0.40 | A | 3.52 | 3.0 | | |

1. Standard wind simulation; $\sigma_{w_g} = \sigma_{V_E} = 3.4$ ft/sec, $U_m = 10$ kts, no vertical gusts.

2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

3. Total height velocity damping, $\zeta_{w_g} - \zeta_{\dot{w}_g} + \zeta_{\ddot{w}_g}$

TABLE A-X

HEIGHT CONTROL FLYING QUALITIES RESULTS FROM THE STUDIES OF CONTROL LAGS
AND DELAYS AND INCREMENTAL THRUST THROUGH STORED ENERGY

Directional Parameters Listed in Table A-I
Pilot Comments Given in Table B-IX

(a) Control lags and Delays

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Parameters | | | | | Pilot | Fixed Base | | Moving Base | |
|-------------------|-------------|------------------------------------|-------|-------|--------------------|-----------|---|-----------------|------------|-------|----------|----------|-------|----------------|----------|----------------|----------|
| | | $X_{\dot{u}}$ | X_u | X_q | $N_{\dot{\theta}}$ | | | $Z_{\dot{u}}^3$ | Z_{uq}^3 | T/W | τ_i | τ_c | | $Z_{\delta c}$ | τ_c | $Z_{\delta c}$ | τ_c |
| HL1 | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | -0.81 ± j1.85 | -0.17 | -0.175 | 1.05 | 0.3 | 0 | A | 3.0 | 2.5 | 3.0 | |
| " | " | " | " | " | " | " | " | -0.175 | -0.175 | 1.05 | 0.3 | 0 | B | 3.0 | 2.5 | 3.0 | |
| HL2 | " | " | " | " | " | " | " | -0.175 | -0.175 | 1.05 | 0 | 0.1 | A | 3.0 | 2.5 | 3.0 | |
| HL3 | " | " | " | " | " | " | " | -0.175 | -0.175 | 1.05 | 0.3 | 0 | A | 3.0 | 2.5 | 3.0 | |
| " | " | " | " | " | " | " | " | " | " | " | " | " | B | 3.0 | 2.5 | 3.0 | |
| HL4 | " | " | " | " | " | " | " | -0.175 | -0.175 | 1.05 | 0.3 | 0.1 | A | 3.0 | 2.5 | 3.0 | |
| HL5 | " | " | " | " | " | " | " | -0.175 | -0.175 | 1.05 | 0.6 | 0 | A | 4.5 | 3.5 | 3.0 | |
| " | " | " | " | " | " | " | " | " | " | " | " | " | B | 3.5 | 3.5 | 3.0 | |
| HL6 | " | " | " | " | " | " | " | 0 | -0.35 | 1.05 | 0.0 | 0 | B | 4.0 | 2.5 | 3.0 | |
| HL7 | " | " | " | " | " | " | " | -0.25 | -0.25 | 1.05 | 0.6 | 0 | A | 2.5 | 2.5 | 3.0 | |

(b) Incremental Thrust Through Stored Energy

| Case ¹ | Basic Conf. | Stability Derivatives ² | | | Real Root | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Parameters | | | | | Pilot | Fixed Base | | Moving Base | |
|-------------------|-------------|------------------------------------|---------------|-------|-----------|---|--------------------|------------|-----------------|-------|--------------|-------|-----------------|----------------|-------------|----------------|
| | | $M_{\dot{u}}$ | $X_{\dot{u}}$ | M_q | | | $N_{\dot{\theta}}$ | Z_{uq}^3 | $Z_{u\delta}^3$ | T/W | $\Delta T/W$ | | τ_{Δ} | $Z_{\delta c}$ | τ_c | $Z_{\delta c}$ |
| HS1 | BC1 | 0.33 | -0.05 | -1.7 | -4.2 | -0.13 | -0.81±j1.85 | 0 | -0.35 | 1.02 | 0 | 0 | 3.0 | 2.67 | 4.0 | |
| HS2 | | | | | | | | 0 | -0.35 | 1.02 | 0.13 | 0.10 | 4.0 | 2.68 | 3.5 | |
| HS3 | | | | | | | | 0 | -0.35 | 1.02 | 0.13 | 0.20 | 3.0 | 2.67 | 3.0 | |
| HS4 | | | | | | | | 0 | -0.35 | 1.02 | 0.28 | 0.10 | 3.5 | 2.67 | 3.0 | |
| HS5 | | | | | | | | 0 | -0.35 | 1.02 | 0.28 | 0.05 | 3.5 | 2.67 | 4.0 | |

1. Standard wind simulation: $\dot{u}_g = \sigma v_g = 3.4$ ft/sec, $u_g = 10$ kts, no vertical gusts.
2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Total height velocity damping, $Z_{uq} = Z_{uq} + Z_{uq}$

TABLE A-XI

DIRECTIONAL CONTROL, FLYING QUALITIES RESULTS

Vertical Parameters Listed in Table A-I
Pilot Comments Given in Table B-X

| Case ¹ | Basic Conf. | V_V | Stability Derivatives ² | | | | Real Roots | Complex Roots $-\zeta\omega_n \pm j\omega_d$ | Amplified, Loop, Delay and Moment Limit Parameters | | | | Pilot | Fixed Base | | Flying Base | |
|-------------------|-------------|-------|------------------------------------|-------|-------|-------|------------|---|--|-------|--------|---------|-------|--------------|------|--------------|------|
| | | | Y_{VR} | Y_V | N_V | N_R | | | R_T | R_C | τ | $d\psi$ | | N_{δ} | IR | N_{δ} | FR |
| D1 | BC1 | 0.005 | 0.33 | -0.05 | -1.7 | -1.2 | -0.13 | $-0.81 \pm j1.85$ | 0 | 1 | 0 | 0 | B | 0.208 | 1.0 | 0.208 | 1.0 |
| D2 | | | | | | | | | -0.5 | 1 | 0 | 0 | A | 0.170 | 1.0 | 0.170 | 1.0 |
| D3 | | | | | | | | | -1.0 | " | 0 | 0 | A | 0.255 | 3.5 | 0.229 | 3.5 |
| " | | | | | | | | | -1.0 | " | 0 | 0 | A | 0.280 | 3.0 | | |
| " | | | | | | | | | -1.0 | " | 0 | 0 | B | 0.275 | 2.5 | | |
| D4 | BC2 | 0.005 | 1.0 | -0.05 | -1.1 | -1.2 | -0.50 | $-0.70 \pm j1.47$ | -1.0 | 1 | 0 | 0 | B | 0.312 | 2.5 | | |
| D5 | | | | | | | | | -0.5 | 1 | 0 | 0 | A | 0.202 | 4.0 | | |
| D6 | | | | | | | | | -0.5 | 1 | 0 | 0 | A | 0.270 | 3.5 | | |
| D7 | | | | | | | | | -0.5 | " | 0.2 | 0 | B | 0.273 | 4.5 | | |
| " | | | | | | | | | -0.5 | " | " | " | B | 0.181 | 5.0 | 0.259 | 1.5 |
| D8 | | | | | | | | | -0.5 | " | 0.3 | 0.1 | A | 0.235 | 4.0 | 0.226 | 5.0 |
| " | | | | | | | | | -0.5 | " | 0.6 | 0 | B | 0.280 | 5.5 | | |
| D9 | | | | | | | | | -0.5 | " | 0.6 | 0 | B | 0.272 | 6.0 | | |
| D10 | | | | | | | | | -0.5 | " | 0.6 | 0.1 | B | 0.248 | 6.0 | | |
| D11 | | | | | | | | | -1.0 | 0 | 0 | 0 | B | 0.305 | 3.0 | | |
| D12 | | | | | | | | | -1.0 | 0 | 0 | 0 | B | 0.294 | 2.0 | | |
| D13 | | | | | | | | | -1.0 | 0 | 0.3 | 0 | A | 0.341 | 3.0 | | |
| " | | | | | | | | | -1.0 | " | " | " | B | 0.313 | 4.0 | 0.275 | 3.5 |
| D14 | | | | | | | | | -1.0 | " | 0.3 | 0.1 | A | 0.258 | 3.0 | | |
| " | | | | | | | | | -1.0 | " | 0.6 | 0 | B | 0.305 | 4.5 | 0.270 | 3.5 |
| D15 | | | | | | | | | -1.0 | " | 0.6 | 0 | B | 0.271 | 4.0 | | |
| " | | | | | | | | | -1.0 | " | " | " | B | 0.237 | 5.0 | 0.258 | 5.0 |
| D16 | | | | | | | | | -1.0 | " | 0.6 | 0.1 | A | 0.308 | 4.0 | | |
| " | | | | | | | | | -1.0 | " | " | " | B | 0.300 | 5.5 | 0.284 | 4.5 |
| D17 | BC1 | 0.005 | 0.33 | -0.05 | -1.7 | -1.2 | -0.13 | $-0.81 \pm j1.85$ | -0.5 | 1 | 0 | 0 | B | 0.232 | 1.0 | | |
| D18 | | | | | | | | | -0.5 | 1 | 0 | 0 | B | 0.238 | 4.0 | | |
| D19 | | | | | | | | | -0.5 | 1 | 0 | 0 | B | 0.233 | 3.5 | | |
| D20 | | | | | | | | | -1.0 | " | 0 | 0 | A | 0.288 | 5.0 | | |
| " | | | | | | | | | -1.0 | " | " | " | B | 0.305 | 5.5 | 0.205 | 7.0 |
| D21 | | | | | | | | | -1.0 | " | 0.13 | 0 | A | 0.230 | 3.0 | | |
| " | | | | | | | | | -1.0 | " | " | " | B | 0.306 | 3.5 | 0.294 | 2.5 |
| D22 | | | | | | | | | -1.0 | " | 0.16 | 0 | A | 0.287 | 3.0 | | |
| " | | | | | | | | | -1.0 | " | " | " | B | 0.306 | 2.0 | 0.294 | 2.5 |

1. Standard wind simulation $\sigma_{V_R} - \sigma_{V_R} = 3.1$ ft/sec, $10 - 10$ kts.

2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

APPENDIX B

SUMMARY OF PILOT COMMENTS FROM UARL PILOT EVALUATIONS

This Appendix presents edited pilot comments for the flight simulator test cases evaluated by UARL pilots. The comments are tabulated for each case according to the subtasks performed by the pilots. For each subtask, comments were solicited according to the questionnaire shown in Table IV. Pilots also made additional comments as they felt necessary.

The comment tables parallel the flying qualities data tables of Appendix A. That is, for each data table in Appendix A there is a corresponding comment table in Appendix B. The comments from the longitudinal and lateral control studies are summarized in Tables B-I through B-VIII as follows: B-I, turbulence effects; B-II, control lags and delays; B-III, control-moment limits; B-IV, control moments through stored energy; B-V, inter-axis motion coupling; B-VI, independent thrust-vector control; and B-VII, rate-command/attitude-hold control. Pilot comments for the height control test cases are summarized in Tables B-VIII and B-IX. Table B-VIII contains velocity damping and thrust-to-weight ratio. Comments from the studies of thrust lags and delays and incremental thrust through stored energy are shown in Table B-IX. The pilot comments from the directional control studies are summarized in the last table, B-X.

TABLE B-I

PILOT COMMENTS FROM THE STUDY OF TURBULENCE INTENSITY

Flying Qualities Results Given in Table A-II

| Task | Conf. Parameters | Alt. Mod. | $\frac{V_{st}}{V_s}$ | PR | Pilot | | | | | |
|------|--|-----------|----------------------|-----|--|---|---|---|--|---|
| | | | | | Selection of Control Characteristics | Maneuvering | Quick Stops | Turn-On-a-Spot | Overall Rating | |
| T1 | B-1 $\frac{V_{st}}{V_s} = 3.0 \text{ ft/sec}$ | A-78 | 0.330 | 2 | Set to achieve desired roll and pitch response for maneuvering. | Disturbance negligible, could perform the air task with desirable precision. Pilot workload quite low. Control actions were very small and low frequency. | Performed quite easily but required a little anticipation to stop at desired point. | Quite easy, required virtually no thrust trim control. | Hover performance very good, required very little pilot effort. | A very good configuration, little control compensation and effort required to perform the task. In general, the configuration has no objectionable features. A. objectionable features in this case, except possibly the low drag parameter, fine attitude characteristics |
| | | | 0.205 | 2 | Selected based on maneuvering and hovering requirements. | Pitch is very easily controlled, don't notice any effects of turbulence. One lateral motion usually in both lateral and longitudinal direction and one stop precisely. | One stop quickly but fairly large attitude changes are required. No problem holding attitude and heading for my quick stops. | Able to remain over the spot quite well. No problem holding attitude. | Could lower quite accurately. Vertical landing was reasonably precise. Dynamics for one axis didn't affect my evaluation of another axis. | |
| | | | 0.313 | 1 | Selected to get necessary attitude response. | No problem, could perform this very accurately, very precisely. | Could perform accurately. | Could remain very precisely over the spot and turn quite rapidly while doing so. Wing tilt control was used to small extent. | No problem. Could be done quite precisely. No later action across dynamics. | |
| T2 | B-1 $\frac{V_{st}}{V_s} = 3.0 \text{ ft/sec}$ | A-78 | 0.250 | 2 | Sensitivity selected primarily for hover. | No difficulty, could stabilize and hold or velocities and stop precisely. | Could stop quite quickly and hold in desired position after stopping. No drag would be desirable. | Could turn over a spot quite accurately. | Not difficult. Could hold hover position accurately while performing the vertical landing. | Thought this was a good case. |
| T3 | B-1 $\frac{V_{st}}{V_s} = 3.0 \text{ ft/sec}$ | A-78 | 0.412 | 1.5 | Set to effect just effects to pitch for roll. | Had to anticipate stopping point due to low drag. Somewhat difficult to stop. Effect of moderate air disturbances on attitude and low translational drag necessitated of considerable pilot compensation. | Requires considerable anticipation to stop. | Reactively easy but did notice gust disturbances in both position and attitude. Little wing tilt was required. | Performance was good, but it did require some compensation to effect the gust disturbances. | Not objectionable features were moderate gust effects on pitch and roll and the difficulty in stopping. Good configuration with a moderate workload. |
| | | | 0.301 | 3 | Selected for precision hover and close control because of relatively high level of turbulence. | Somewhat difficult to stabilize desired velocities because of the turbulence. Some problems stopping precisely and hovering. Could perform this part of the task fairly well, though. | No real problem with the quick stop. | Slightly difficult because of the gusts. Once attitude characteristics better helped. | Precision hover is moderate, difficult, must pay attention to gusts and may experience attitude changes. Able to land the stop precisely. | |
| | | | 0.297 | 3 | Set to get the attitude response I desired. | Not difficult, good response to all the control inputs. Large speed stability had side effects, sometimes blown laterally when maneuvering longitudinally. | No problem, can stop very quickly. | Difficult but main attitude control very fine giving no time to concentrate on position. | Could hover quite well, but large V_{st} , but no way could land well. No problem. | |
| T4 | B-1 $\frac{V_{st}}{V_s} = 3.0 \text{ ft/sec}$ | A-78 | 0.307 | 2 | Set mainly for attitude changes during maneuvering. | Somewhat difficult to achieve translational motion, requires rather large attitude changes. One stop with pretty good degree of precision. | Difficult to perform, just time to get up to speed and then large attitude changes are required to arrest velocity. | Requires trim changes with the wing. Also the gas blown around a lot in position. Requires quite a lot of attention. | Fairly easy, although the side push one around in position. Landing and takeoff not difficult. | Biggest objection is high drag of aircraft and the associated large attitude changes required to maneuver. Only moderately objectionable features were effects of the large V_{st} in hover and turn-on-a-spot. Manageable features were the good dynamics and the position holding. |
| | | | 0.306 | 3 | Selected primarily to control hovering position. | Easy response to control inputs. Able to initiate motion and hold desired velocities without problem. However somewhat sluggish in position response. | Couldn't stop as quickly as would like. Somewhat difficult to stabilize velocity. Inverse attitude changes not really required. | Able to remain over the spot fairly well. In spite of the large V_{st} , could still make dynamic hold. | Could hover precisely without any difficulty and perform vertical landing, precisely. No translational effects objectionable. | |
| | | | 0.276 | 4 | Selected to get control over attitude. | Easy to control. Likes the area parameter, learned to stop slowly. All hold was well stopped. | Could stop quickly, but time very near to normal and the area parameter had to stop. | One is successful, if time is taken. Good wing tilt action. | Could hover precisely and land without too much difficulty. No interference in the dynamics. | |
| T5 | B-1 $\frac{V_{st}}{V_s} = 3.0 \text{ ft/sec}$ | A-78 | 0.250 | 2 | Selected to reverse from pitch attitude roller for hover. | Good response to control inputs. Able to initiate and hold motion very easily. No problem stopping precisely and hovering at the hover. | One stop as quickly as would like. Somewhat difficult to build up the climb. | Able to remain over the spot fairly well. Attitude control a problem but large drag parameters caused trouble, used trim a lot to stop. | Could hover precisely although were relatively large position attitude changes from hover. Could control hover adequately for vertical landing. A transition between dynamics. | Only objectionable feature was turbulence during or large drag parameters during hover and turn-on-a-spot maneuver. |
| T6 | B-1 $\frac{V_{st}}{V_s} = 3.0 \text{ ft/sec}$ | A-78 | 0.205 | 1.5 | Set primarily for trim during maneuvering. | Attitude control very good, little gust disturbance on attitude. Requires large attitude change to get desired velocity, but was not really a problem. Note that the aircraft would in position. | Control inputs rather large but requiring no problem. | Difficult only because the gas is pushed the aircraft around in position. Large wing tilt trim control are required. | Performance not too good because of gust disturbance or position compensation. Attitude holding control activity relatively low frequency. | Disturbance in position was not objectionable. Attitude was good. Thought this was a good case. Only objectionable feature was turbulence during or large drag parameters. Attitude was not really objectionable. It is made larger, makes attitude changes in position. In position. In position. |
| | | | 0.250 | 1 | Selected to give desired attitude response in hover. | Longitudinal position response. Attitude control very fine. Tended to lose position in side normal to maneuver direction. | Could stop quickly at difficult to hold position after stopping. | Able to perform this without real. Once attitude characteristics were somewhat better, the situation would be better. | Somewhat difficult because of large side effects of drag parameter. It is made larger, makes attitude changes in position. In position. In position. | |

TABLE B-I (Continued)

| Task | Test Parameters | Pilot's Initial Rating | Pilot's Final Rating | Pilot's Comments | Pilot Comments | | | | | |
|------|--|------------------------|----------------------|------------------|---|---|--|---|---|---|
| | | | | | "Alertness" or "Control" Sensitivity | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 76 | RC $\dot{\phi}_0 = \dot{\phi}_g = 0.2 \text{ ft/sec}$ | A-FB | 0.375 0.291 | 3 | Selected to enable control of gusts | Quite difficult, would get blown off laterally when maneuvering longitudinally and vice versa. Motion was initially disorienting because it was chiefly linear motion with little attitude motion because of dynamics. | Could stop as quickly as would like but aircraft too responsive to position gusts | Difficult, must do it very, very slowly. Used a lot of wing tilt. Requires concentration. | Could not hover particularly accurately. Could correct position motion, but very difficult to get back to desired lower position. Could land alright, but it was difficult. Used the trim control to kill velocities. No problem with secondary dynamics. | Gusts acting on large drag parameters very objectionable. Attitude well damped, easy to control, however. |
| 77 | RC $\dot{\phi}_0 = \dot{\phi}_g = 3.4 \text{ ft/sec}$ | A-FB | 0.333 0.331 | 3 | Selected for maneuvering test to control roll and pitch disturbances. | Response to control inputs good. Stopping at desired point required a little anticipation in reverse roll. Could maintain ground track fairly well. | No problems generating velocity. Stopping required some anticipation. | Only problem was effect of nose wheel which required small change in wing tilt. Must concentrate to perform the turn. | Performance very good with little control action required. Landing no problem. | Configuration fairly good. Gust disturbances to roll and pitch did require a bit of pilot attention. |
| | | B-FB | 0.276 0.225 | 4 | Selected to enable pilot to move the aircraft around in position. | Control response good. Could stabilize and hold velocities well and stop precisely. Some difficulty in initiating motion. | No problem, could stop quite quickly. Attitude was easy to control. | Most difficult without the large drag parameters resulted in large position disturbances. Used large trim changes and had to be very careful with them. | Precision hover and vertical landing not difficult. The lateral (longitudinal) drag parameter affected the ability to control longitudinal (lateral) position. | Major objectionable feature was the effect of winds on the large drag parameters. Favorable feature was that attitude control was quite good. |
| | | B-HB | 0.350 0.301 | 3 | Selected to overcome attitude damping and enable pilot to change attitude rapidly enough to counteract the effects of drag parameter. | Could maneuver quite adequately. May to stop at the corner because of the large drag parameter and low gusts. | May to stop very quickly, the drag parameters helped. | Difficult, but was done slowly and seemed to be able to handle it pretty well. Used a lot of wing-tilt angle. | Could hover fairly precisely. Gust disturbances low. Could land quite well secondary dynamics no problem either. | Objectionable features - possibly the effects of drag parameter in the turn-over-a-spot maneuver. Favorable feature - good attitude response, generally low response to the turbulence and the drag parameters helped the maneuvering and quick stop. |
| 78 | RC $\dot{\phi}_0 = \dot{\phi}_g = 5.0 \text{ ft/sec}$ | A-FB | 0.450 0.350 | 3 | Selected to achieve the desired attitude response. | Good attitude response, but the only way kind of sluggish. Could stabilize and hold velocities and stop precisely. | Could stop quite quickly. Relatively large attitude changes were required. | Most difficult of all the subtasks because of the concentration and activity required to counteract the nose wheel acting through the speed-stability parameter and hold my heading spot. | Modestly difficult, substantial disturbances in position, large attitude changes required to correct them. No interaction. | Objectionable feature - attitude response to gusts through speed stability which lead to large position disturbances. Favorable feature - good attitude dynamics. |
| 79 | RC $\dot{\phi}_0 = \dot{\phi}_g = 0.2 \text{ ft/sec}$ | A-FB | 0.616 0.366 | 6 | Set to control very large gust disturbances | Difficult to initiate motion, hold heading and stop precisely because of gust effects. | Difficult to stop because of gust effects. Large attitude changes required to control position. | Difficult to hold position. Great deal of coordination between wing tilt and control input required. Difficult to perform. | Difficult, require extensive amounts of control input. Large attitude changes result from gusts and control inputs. | Most objectionable feature was the very high gust sensitivity and lack of attitude damping. Very high workload and very high degree of concentration required to maintain control. |
| | | B-FB | 0.513 0.434 | 5 | Selected to handle turbulence effects on attitude and to correct for the large position disturbances introduced by turbulence. | Effects of turbulence on attitude and position were significant, had to work hard to hold desired velocities. Difficult to maintain the position while performing the part of the maneuver and vice versa. Large control deflections required periodically. | Could stop quickly but had to watch position carefully afterwards. Rapid control motions required. | Able to remain over the spot because of good attitude dynamics. Free with a large % of hover over the spot. Reasonably well. Had to be careful, used the trim button a good deal. | Attitude dynamics good, allowed pilot to hover fairly well. Biggest problem was effect of turbulence on the drag parameters, made vertical landing difficult. No noticeable interaction. | Objectionable features - effects of turbulence on attitude and position. Favorable feature - Good attitude control response. |
| | | B-HB | 0.375 0.297 | 6 | Selected to overcome gust effects on attitude. | Blow all over, sharp rough gust inputs, attitude oscillates around wildly. Can't perform well. | Attitude control workload overwhelming because of gusts. Precise control impossible. | Blow off position by the large gusts, could not change wing tilt quickly enough to hold it. Made full pull on controlling pitch, roll attitude. | Could not hover precisely, could keep only within 15 ft of square. Landing hazardous, very difficult. Large interactive effects between pitch and roll. | Very difficult to control and maneuver. Needs more damping to reduce response to turbulence. |
| 80 | RC $\dot{\phi}_0 = \dot{\phi}_g = 1.4 \text{ ft/sec}$ | A-FB | 0.373 0.320 | 4 | Set to control gust disturbances on roll and pitch attitude. | No problem initiating or stopping motion. Could remain within the ground track fairly accurately and hold heading and attitude fairly well. | No particular problem, except constant trim had to be held in to maintain velocities. | Performance good, very little wing tilt trim required. Most of the workload from controlling attitude disturbances. | Good performance. | Dynamics were fairly good, more pitch rate and roll rate damping desirable to reduce response to turbulence. |
| | | B-FB | 0.343 0.190 | 5 | Selected to gain control over attitude | Disagreeable attitude response to control inputs. Difficult to stabilize attitude which also affected my ability to stabilize maneuvering velocities. Could stop fairly precisely but this excited undesired and excessive attitude motions. | Could perform quick stops without great difficulty. Attitude motions were larger than would like. | Difficult to control roll attitude for this subtask. | Could hover fairly precisely and could control hover position sufficiently well to perform a reasonably landing. Attitude dynamics in roll affected my ability to control pitch and vice versa. | Most objectionable feature was the lack of attitude damping. |
| | | B-HB | 0.375 0.297 | 5 | Not too difficult. Did get blown off track, but not frequently. Gust effects significant on pitch and roll. | Not too difficult. Did get blown off track, but not frequently. Gust effects significant on pitch and roll. | No significant problems. Drag parameters small which made it somewhat difficult to arrest motion. | Not too difficult because attitude damping sufficient. Noticeable gust effects on attitude, though. | Did not hover precisely and did a good job landing. Some interaction between pitch and roll control. | Objectionable feature was the gust effect on attitude. More damping desirable to reduce gust response. Favorable features - the low drag parameters made the hovering and turn subtasks less |

TABLE B-I (Continued)

| No. | Altitude Parameter | Altitude Rate | Altitude Rate | Altitude Rate | Pilot Comments | | | | | |
|-----|--|------------------|------------------|------------------|---|--|---|--|---|--|
| | | | | | Selection of Control Activities | Maneuvering | Stick Force | Turn-Over-Point | Attitude Power, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 111 | NO $\dot{\alpha}_g, \dot{\alpha}_g$ 4.0 ft/sec | 0.426 | 0.340 | 6 | Selected to control attitude response to gusts and to overcome the lack of damping. | Attitude needs more damping. Turbulence really buffeted me about. Able to stabilize and hold velocity fairly well, but required a great deal of attention. Could stop precisely. | Can stop quickly, but very large attitude changes result. Have some difficulty stabilizing attitude. | Able to remain over the spot quite well. Low drag parameters helped. Attitude required a significant amount of attention. | Could hover adequately with effort and could land alright. Attitude wasn't as controllable as it should be. Some interaction between the attitude in one axis and my ability to control another axis. | Primary objectionable feature was the lack of attitude damping and its response to turbulence. Favorable feature - low drag parameters helped in hover and turn. |
| 112 | NO $\dot{\alpha}_g, \dot{\alpha}_g$ 0.2 ft/sec | 0.445 | 0.322 | 5 | Selected to control attitude gust response and control response | Difficult to initiate and hold velocity because of the attitude characteristics, could not maneuver laterally and hold position. Attitude seemed unpredictable. | Could stop relatively quickly but had difficulty holding desired position of the other axis. Large attitude changes involved in this situation. | Able to maintain position fairly well because of low drag parameters. Attitude control quite difficult. | Able to hover fairly well but large attitude excursions involved. Very difficult to accomplish vertical landing. Pitch attitude control difficult affected by ability to control roll and vice-versa. | Attitude characteristics quite objectionable, spring characteristic absorbing favorable features - low drag parameters. |
| 113 | NO $\dot{\alpha}_g, \dot{\alpha}_g$ 3.4 ft/sec | 0.445 | 0.295 | 5 | Selected to counteract gust disturbances on attitude | Considerable effort required to control attitude gust disturbances. Large attitude changes necessary to initiate and sustain motion. Difficult to hold desired velocity, but could stop precisely. | Difficult to generate velocity. Could stop fairly well, although large attitude changes were required. | Gust disturbances on attitude and position annoying, but performance not too bad. Required concentration. | Performance fairly good, but considerable stick activity due to attitude and position gust disturbances. Landing not too difficult. | Some attitude damping and high drag objectionable in hover, although it did provide translational damping. |
| | | | | 5 | Selected to control position disturbances and for maneuvering | Difficult because attitude was compromised. Could not maintain a precise attitude angle or a steady velocity. Could stop fairly precisely. | Difficult to attain velocity, but could stop quickly. | Difficult, had to be very careful with my control inputs and concentrate. Used trim almost constantly. | Could hover fairly accurately. Would like better control over attitude for landing. Large drag parameter did affect ability to control longitudinally and vice-versa. | Two objectionable features were the large drag parameters and the low damping levels in pitch and roll. |
| | | | | 6 | Selected to control attitude response to stick inputs and gusts. | Not too difficult, lack of attitude damping affects ability to maintain constant velocity. Lateral speed-stability effects very evident through action. | Can accomplish, but could use more attitude damping. | Very tough, large attitude changes were required to concentrate too much on pitch and roll to turn precisely. | Can hover well but must pay attention. Notice helps to keep from overcontrolling. Can land adequately. | Notice leads to use of smaller, more precise control inputs. Take-off and landing simulations very realistic. |
| 114 | NO $\dot{\alpha}_g, \dot{\alpha}_g$ 3.8 ft/sec | 0.445 | 0.363 | 7 | Selected to get with and roll attitude under control | Need more damping in both pitch and roll. Difficult to initiate motion and to maneuver. Couldn't hold ground track well. | Can stop quickly but large attitude changes result. Difficult to control attitude. | Can't remain over the spot well. That was with the angles required. Large pitch and roll angles. | Precision hover is manageable, but large attitude angles required. Landing tough because of attitude, longitudinal dynamics made it difficult to control laterally and vice-versa. | Objectionable feature - the lack of having |
| | | | | 7 | Selected to get attitude under control. | Acceleration response to control inputs. Gust response in attitude and position a major annoyance. Couldn't really control precisely. | Could stop fairly quickly. Large drag parameter helped. Develops large attitude angles, though. | Could hold position fairly well, but very difficult task. Must be slow, use trim tilt constantly. | Could hover without too much difficulty. Lot of attitude motion. Landing alright but had to use trim tilt some situation. | Primary objectionable feature - large gust inputs, low damping, quite acting on the drag parameter. Favorable features - none. |
| 115 | NO $\dot{\alpha}_g, \dot{\alpha}_g$ 2.2 ft/sec | 0.541 | 0.352 | 9 | Selected to counteract very large gust disturbances and to maintain control | All aspects of the attitude extremely difficult. Primary effort was to maintain control. Difficult to stay within boundaries of maneuvering area and to hold heading and altitude. | Very difficult to control. | Difficult to hold position, but not desired. Turn rate because of large gust disturbances in pitch and roll. | Manageable. Precise pitch control activity required. Landing required because of difficulty in holding both position and level attitude. | Objectionable features - large gust response in position and attitude and the small levels of damping. No favorable features. |
| | | | | 6 | Selected to achieve control over attitude and eliminate gust response | Disagreeable response to control inputs and gusts, needs much more damping. Tough to initiate, stabilize velocities and difficult to stop. | Can stop quickly, but use large attitudes. Large roll control requires use of also. | Able to remain over a spot but requires much effort and attention. Used trim about constantly. Attitude control was difficult. | Periodically turn off position and level attitude angles required to arrest motion. Precise isn't adequate for vertical landing. The dynamics from longitudinal axis did affect in control of lateral axis, and vice versa. | Objectionable features - large gust response in position and attitude and the small levels of damping. No favorable features. |
| 116 | NO $\dot{\alpha}_g, \dot{\alpha}_g$ 3.4 ft/sec | 0.445 | 0.340 | 5 | Selected to counteract maneuvering effects | Could be maneuvered with considerable concentration. Pitch and roll were slightly underdamped. Could stop fairly well and I was at desired points. | Performed fairly well but not control gust effects. | Some difficulty holding position. Required concentration to perform. Could stop fairly well on preselected heading. | Could perform better with this precision, required concentration. | Lack of roll and pitch damping objectionable. |
| | | | | 6 | Selected to achieve control over attitude and eliminate gust response | Could perform fairly well. Would prefer more damping in both pitch and roll and to concentrate more with attitude than desirable. | Requires more concentration and attention to perform than would prefer. In large attitude oscillations. | Could stop fairly well on preselected heading. | Could perform better with this precision, required concentration. | Objectionable features - lack of damping in pitch and roll oscillations. Response to turbulence was that would like favorable features the low drag parameters. |

TABLE B-I (Concluded)

| Case | Conf. Parameters | Stick- rate noise | $\frac{V_{st}}{\delta a}$ | PK | Pilot Comments | | | | | |
|------|---|-------------------------|---------------------------|----|--|---|---|--|---|---|
| | | | | | selection of control sensitivities | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Pilot's Comments |
| T16 | NC3 $\dot{\phi}_g, \dot{\psi}_g =$ 3.0 ft/sec | B-7B | 0.407 0.280 | 6 | Selected to overcome lack of damping and control response to turbulence. | Required a significant amount of control activity. Had to maneuver slowly. Lack of position damping annoying. | Need large attitude changes to stop. Had to roll out at just the right moment to stop and stabilize position. Need position damping. | Could perform fairly well because of the low drag parameters. Had to be careful, however. | Could hover fairly well, but attitude motion re- quires attention. Verti- cal landing not too difficult. Dynamics from one horizon- tal axis did affect the other. | Objectionable features - low attitude damping, little more drag para- meter needed. |
| T17 | NC3 $\dot{\phi}_g, \dot{\psi}_g =$ 3.0 ft/sec | B-7B | 0.439 0.373 | 6 | Selected to overcome lack of damping. | Good position response. Difficult to control attitude, tended to overshoot desired angle, required significant compensation. | Could stop quickly but really had to watch attitude. Some tendency to drift off longitudi- nally when maneuvering laterally. | Able to remain over the spot because of the small drag parameters. Needed large stick inputs, developed some very large pitch and roll rates. | Could hover quite well, but lots of pitch and roll motion. Couldn't hold position precisely during the landing. Pitch dynamics do affect ability to control roll. | Objectionable features - the low level of atti- tude damping. Favorable features - the small drag parameters. |
| T18 | NC3 $\dot{\phi}_g, \dot{\psi}_g =$ 3.0 ft/sec | B-7B | 0.467 0.350 | 6 | Selected to control atti- tude gust response. | Disagreeable control response inputs. Needs damping in pitch and roll. Difficult to stabilize, hold velocities and stop precisely. | Can stop quickly, but large attitude changes required. Takes some time to stabilize atti- tude after coming to a stop. | Able to remain over the spot fairly well because drag parameters were small. Attitude control difficult, had to con- centrate. | Could hover fairly well but large control motions required, must concen- trate. Difficult to main- tain position during verti- cal landing. Dynamics for roll did affect pitch control and vice-versa. | Lack of attitude dam- ping very objectionable. Difficult to control gust response. However, drag helped in the turn-over-a-spot and hover subtasks. |

TABLE B-II

PILOT COMMENTS FROM THE STUDY OF LONGITUDINAL AND
LATERAL CONTROL SYSTEM LAGS AND DELAYS
Flying Qualities Results Given in Table A-III

| Case | Conf. Parameters | Stability | $\frac{V_0}{V_{00}}$ | PR | Pilot Comments | | | | | |
|------|--------------------------------|-----------|----------------------|-----|---|--|--|--|--|---|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 111 | RC1 $\tau_a = \tau_b = 0.1$ | B-FB | 0.293 0.268 | 2 | Selected to get the attitude response wanted. | Not difficult. Mostly damped attitude response, able to select and stabilize velocities with no problem. Stop precisely. No large evident in the attitude response. | Not difficult to perform once control attitude was previously. One problem this task very well. | Not difficult to perform. Wing tilt control not used much. | No problem, one hover quite precisely with very little control input. Vertical landing also no difficulty. | Fine case. Attitude is very nicely correlated with the stick inputs, no noticeable lags, one control quite well. |
| 112 | RC1 $\tau_a = \tau_b = 0.3$ | A-FB | 0.294 0.260 | 3 | Set to achieve desired attitude response for the air taxi. | Performance was good, only slightly objectionable feature was that commanding an attitude change caused slight oscillation, also slight lag in attitude response. Out efforts minimal, control motions low frequency not small in amplitude. | Performance was good, although slight lag in attitude response when commanding rapid attitude changes. | Very easy and very little thrust rotation control required. | Hover required very little effort, performance good. | Only slightly objectionable feature was small lag in attitude response and small oscillatory motion when commanding a rapid attitude change. |
| | | B-FB | 0.130 0.251 | 2.5 | Selected to get the attitude response to overcome a slight lag. | Air taxi not difficult. Could perform precisely. Some slight oscillation when rolling or pitching in and out of maneuver, but nothing difficult to estimate. No lack of control power. | Could perform precisely, no problem. Again slight oscillation of pitch and roll, but easily damped. | Quite easy to perform. Didn't use wing tilt control much. | Relaxed inputs in hover, could hover quite precisely. Vertical landing also not difficult. | Nicely damped, low response to turbulence, lag effects small, some slight tendency to oscillate in pitch and roll but easily damped. |
| 113 | RC1 $\tau_a = \tau_b = 0.6$ | A-FB | 0.355 0.352 | 2 | Selected to give desired attitude response. | The air taxi relatively easy. Response to control inputs good about all cases. May be initiate maneuver although some anticipation required to stop at a desired position. Could stop and hold hover with good degree of precision. Only small attitude changes required. | No problem, although some position anticipation required to stop at desired point. | Relatively easy. Had to use a small amount of wing tilt control to offset the main wind effects. | Very easy to hover, required only very small control inputs. | Liked the good attitude control and the very low response to turbulence. Pilot workload quite low. |
| | | B-FB | 0.139 0.268 | 3 | Selected to get the attitude response. | Air taxi no problem. Could perform both X and Y maneuver tasks precisely and hold velocities steady and arrest motion without too much difficulty. Slight tendency to oscillate at the end of maneuver, had to compensate for this but it wasn't difficult. | Could stop quite accurately and didn't experience any real large attitude changes. Again, some tendency to oscillate in pitch and roll, had to worry about this a bit. | No difficulty here. Could perform quite well. Wing tilt control wasn't used a great deal. | Could hover very precisely with relaxed slow control motions. Vertical landing easy to perform. | Little bit of oscillation in pitch and roll but not a big problem. Nice relaxed response, low response to turbulence, nicely damped configuration. |
| | | B-MD | 0.179 0.268 | 3 | Selected to control response to turbulence and also pitch oscillations. | Couldn't perform air taxi as precisely or as easily as desired. Difficult to control attitude and to hold a desired velocity. Could not stop very precisely. | Some problem as air taxi, just couldn't seem to control position rates as accurately as desired. | Some problems were controlling position while turning. Did try to use the wing tilt control, but lost position. | Hover wasn't too great a problem because didn't introduce large control inputs. Didn't get into any oscillations. Could land alright. Some interaction between pitch and roll. | The oscillatory response in pitch and roll annoying. Could not seem to stabilize pitch and roll particularly well while maneuvering and doing quick stops. |
| 114 | RC5 $\tau_a = \tau_b = 0.1$ | B-FB | 0.302 0.262 | 2 | Selected to give desired response. | Good response to control inputs, very predictable attitude response, no problems at all in coming up to a desired velocity and holding it and stopping at desired position. Liked the large drag parameter here. Didn't worry too much about being blown about. | Could stop very quickly and precisely. Had no problem stabilizing on rate. | Attitude so easily controlled and quite low enough so that even with high drag didn't have difficulty. | No problem in hover. Occasionally would get blown off position some, but no real difficulty. | No real objectionable features. The large drag made it somewhat difficult to attain lateral and longitudinal velocities. Good attitude response, drag made it easy to stop precisely and rapidly. This is a good case. |
| 115 | RC5 $\tau_a = \tau_b = 0.3$ | B-FB | 0.296 0.254 | 2 | Selected to get the response for roll and pitch. | Could perform air taxi very well. Attitude was well damped, very predictable and no oscillations. Could stop accurately due to the fairly large drag. Quite no annoyance. Very good case. | Could stop quite precisely, no problem. Large drag helped stopping. | Performed this subtask very well. Could take eyes off attitude and look at wing tilt indicator with no problem. Could tilt the wing rapidly, this compensated very nicely for the main wind. | Hover no problem, one was vertical landing. | No objectionable features. Because of good attitude characteristic the high drag was no problem when performing the turn. |
| 116 | RC5 $\tau_a = \tau_b = 0.6$ | A-FB | 0.241 0.312 | 3 | Selected to get adequate attitude response. | Relatively good position control during air taxi but required relatively large attitude changes to get aircraft response in translation. Could hover fairly well at the corners and could hold heading and attitude accurately because vestibular in pitch and roll was low. Control deflections were small. | Very easy to perform because of the high drag of the configuration. | Difficult is that considerable wing tilt control had to be used to offset the main wind effects, but with anticipation performance was fairly good. | Hover was fairly good although with the high drag got pushed around in position quite often. This degraded by rating slightly. | The only objectionable feature was the large disturbance in position through the drag of the aircraft while hovering. |
| | | B-FB | 0.137 0.363 | 4 | Selected to gain the attitude response needed to overcome lags. | Could perform air taxi fairly well. Did notice that when maneuvering laterally tended to get blown off somewhat in longitudinal position, but handled maneuver fairly well. Some fairly small oscillations in attitude that were difficult to damp, but no great problem. | No problem with this task, could come to desired spot and stop fairly accurately. Rather large drag helped. | Did this quite well. Attitude was sufficiently well damped and controllable that could switch vision between wing tilt angle and display. | With rapid wing tilt could rotate thrust quickly so as to keep fairly decent control over hover position. Vertical landing no problem. | Only objectionable feature was small lag in response but that led to low level oscillations which were fairly persistent and required some attention. Well damped attitude response, low response to turbulence and the large drag helped in maneuvering and quick stops. |

TABLE B-II (Continued)

| Case | Cof. Parameters | Pilot's Mode | $\frac{V_{0.5}}{V_0}$ | VR | Pilot Comments | | | | | |
|------|--|--------------|-----------------------|-----|---|---|---|---|--|---|
| | | | | | Selection of Control Sensitivity | Maneuvering | Quick Stops | Turn-Over-a-Spot | Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 115 | 205 $\frac{V_0}{V_0} = \frac{V_0}{V_0} = 0.5$ | B-30 | 0.308 0.262 | 3 | Selected to get desired response in pitch and roll. | Could perform air taxi quite precisely. Attitude very well damped, very predictable. Could stop precisely and control hover and maneuvering velocities very well. Had a small problem getting blow off desired track occasionally but that was fairly easy to correct. | No problem. Could perform these quite smoothly and accurately. | Could remain over the spot very well. Did use wing tilt control a good deal because of the high drag. | Hover not difficult. Had to watch the gusts though to get blow off in position. Vertical landing easy. Control activity relatively low during hover and landing. | Only minor objectionable feature was getting blow off position periodically when trying to maneuver and hover. Fine attitude characteristics, well damped, low response to turbulence, comfortable case. |
| 117 | 205 $\frac{V_0}{V_0} = \frac{V_0}{V_0} = 0.1$ | B-75 | 0.424 0.313 | 2 | Selected to get the response needed to overcome damping. Wide range of control sensitivities seemed acceptable. | Air taxi no problem. Good response to the control inputs, low response to turbulence, and the high drag helped in stopping and starting precisely and in holding desired velocity. | No problem. | Good attitude characteristics helped overcome the high drag and also the high rate of change of wing tilt which is now available helped to control lowering position quite accurately. | Could hover quite accurately. Also, could land without difficulty. | No objectionable features. Maneuvering features were the good damping and high drag which helped in maneuver and quick stops. |
| | | B-30 | 0.415 0.345 | 4 | Selected to attenuate the gusts. | Air taxi not difficult to perform. Position motions were nicely damped due to large drag parameter, attitude was quite predictable. The effects of gusts were somewhat large but didn't affect any great difficulty. | Could set up a desired velocity and maneuver quite well, stop very precisely without any trouble. Attitude control well damped, very predictable. | Was able to remain over the spot without any difficulty. Had to use wing tilt angle a good deal because of high drag but not difficult to perform this task. | Hover is probably the most difficult task to perform. Could hold position fairly well but it required appreciable control activity. Good deal of control activity needed for vertical landing. | Objectable feature was the somewhat high response to turbulence. Position was nicely damped, attitude dynamics were good. |
| 118 | 205 $\frac{V_0}{V_0} = \frac{V_0}{V_0} = 0.3$ | A-75 | 0.399 0.349 | 2.5 | Set to get desired attitude response. Attitude dynamics well damped and easily controlled. | Air taxi fairly easy except that fairly large attitudes required to initiate motion, however can stop fairly precisely at desired point. Control deflections relatively small. | Relatively easy to perform except that large attitudes are required to initiate the action. | Fairly easy except that concentration is required to offset the mean wind. Considerable thrust rotation is required to maintain hovering position in the presence of the mean wind. | Hover performance very good with very little pilot attention required. | Attitude control is good and there is no evidence of control lags in the system. Most objectionable feature is high drag. In particular the gust effects at position disturb the aircraft. |
| | | B-75 | 0.349 0.277 | 3 | Selected to counteract the damping effects. | Air taxi no problem. Did notice some slight oscillation in roll and pitch in response to control inputs, but not large and were easily controlled. Able to perform maneuver quite accurately. | Could stop quite quickly and had no problem setting up and maintaining a constant rate during the quick stop. Large speed stability aided stopping rapidly and precisely. | Able to remain over the spot quite well. Increased rate on wing tilt helps this maneuver. | Could hover precisely with fairly limited control inputs. Vertical landing no problem. Used wing tilt to help with longitudinal position control. | Only objectionable feature was the slight oscillation in response to roll and pitch inputs, but not particularly bad. Lots of damping, low response to gusts, and the high drag helped maneuvering and didn't seem to degrade lower or the turn maneuver. Had to closely watch wing tilt angle in the turn. |
| | | B-30 | 0.421 0.329 | 5 | Selected to control aircraft response to turbulence. | Response to control inputs was fairly predictable and probably acceptable, but the turbulence effects were too large. Could perform the task but really had to concentrate. Difficult, had to constantly be taking care of the effects of gusts and avoiding to make sure wasn't blown off. Difficult to hold the desired velocity. | Could perform the task but really had to watch for the effects of gusts. | Did this fairly well but had to do it slowly because of the effects of the gusts. Got into some fairly large and relatively oscillatory attitude changes. Used wing tilt control a good deal. | Hover feelings about ability to hover. Sometimes seemed to be able to do it fairly well, other times not so well. Could hold it alright. Lot of control activity in both hover and landing. | Primary objectionable feature was response to turbulence. |
| 120 | 205 $\frac{V_0}{V_0} = \frac{V_0}{V_0} = 0.5$ | A-75 | 0.407 0.322 | 4 | Set for adequate attitude control. | Air taxi fairly easy except with high drag required relatively large attitudes to initiate motion. Could stop action relatively easy and hold hover position with very small control deflections. | No problem except in getting the aircraft moving, but didn't stop very accurately at desired spot. | Required satisfaction with thrust position control attitude control required just a slight amount of attention. Did use wing tilt control to hold hovering position while making the turn. | Hover performance good, but did get blow around a little bit in position. | Attitude control was fairly good but it did require a little attention to prevent it from becoming oscillatory and from drifting off desired heading. |
| | | B-75 | 0.410 0.344 | 5 | Selected primarily to get the response desired. Difficult time getting proper attitude response. | In general, could perform the task fairly well. Air taxi was no problem. Attitude seemed predictable, and the high drag helped. | No problem. | Could perform this fairly well. Didn't have to worry too much about stopping and the large rapid wing tilt rate helped in maintaining position over the spot very well. | Could hover accurately, no problem. Vertical landing wasn't particularly difficult. Only thing annoying was the difficulty in getting the control response that was needed. | No real objectionable features, some slight oscillation in pitch and roll. The general good attitude characteristics are favorable features. |
| 1210 | 202 $\frac{V_0}{V_0} = \frac{V_0}{V_0} = 0.1$ | B-75 | 0.409 0.320 | 4 | Selected to control the speed-stability effects and the response to turbulence. | Response to control inputs was predictable although it was slightly oscillatory and did notice some response to gusts. Able to initiate motion and to stabilize and hold desired velocities without any problem. Could stop in level and hover accurately in the maneuvers. | No problem seen. Did notice a slight response to turbulence and some slight oscillation in pitch and roll. | No problem. Occasionally generated some fairly large and oscillatory roll and pitch motions, but was able to maintain position over the spot very well. | Had difficulty with hover or landing. | The only objectionable feature seemed to be a slight oscillatory tendency in pitch and roll and some response to turbulence. Noticed the effects of speed stability when maneuvering, but these were easily compensable. Attitude response was fairly predictable and could perform all tasks without too much problem. |

TABLE B-II (Continued)

| Task | Def. Parameters | Pilot-Inst. Note | V_{AS} - V_{AS} | IF | Pilot Comments | | | | | |
|------|-------------------------|------------------|---------------------------|-----|---|--|---|---|--|---|
| | | | | | Selection of Control Activities | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 1110 | NC $T_0 = T_A = 0.1$ | A-MB | 0.390 0.296 | 5.5 | Selected to control attitude because of poor damping and also to control attitude response to turbulence. | Performed the task fairly well but there were attitude oscillations. Attitude needs more damping for more precision control. | Was able to stop quickly, but would prefer more attitude damping. Attitude response to turbulence quite large and difficult to hold velocities. Developed fairly large attitude angles when arresting motion. | Was able to remain over the spot fairly well due to a low drag. However, did develop some fairly large oscillations in attitude. Didn't use wing tilt control too much. | Able to hover quite precisely, held hover position without too much trouble. However, control activity was reasonably high during hover and landing tasks. Some lateral action between dynamics but not too bad. | Would prefer to see more damping in pitch and roll, less response to turbulence, and more predictability in the response to control inputs. Configuration was controllable and could perform the task but not as easily as desired. |
| 1111 | NC $T_0 = T_A = 0.3$ | A-FB | 0.584 0.257 | 5 | Set to control and stabilize pitch and roll attitude. | Air taxi maneuver requires some work in that attitude is lightly damped and fairly gust sensitive. No problems initiating action but small amount of anticipation required to stop at desired points. Gust disturbances on attitude seemed to be the biggest problem. | Can be performed readily however some anticipation is required to stop at desired points. | Hardest workload is in offsetting gust disturbances on attitude and maintaining attitude stability. Very little wing tilt was used in "off" position. | Hover performance was fairly good but attitude control required some attention. | Most objectionable features of this case were (1) the control lag in both pitch and roll and (2) the gust disturbances on pitch and roll. More damping would be desirable. Adequate performance requires considerable pilot concentration. |
| | | B-FB | 0.347 0.270 | 5 | Selected to control oscillations in pitch and roll to get attitude response desired. | Problem here was oscillatory nature of roll and pitch, although never felt control would be lost. Was able to stop fairly precisely and to control velocities pretty well, but did have to pay a significant amount of attention to pitch and roll. | No great problem here, but attitude tended to wander around and had to pay attention to it. | Was able to remain over the spot quite well, but pitch and roll required attention. Oscillatory nature of pitch and roll was an annoyance. | Hover wasn't any great difficulty, could hold it pretty accurately but did get some moderately large oscillations because of their oscillatory nature. Could land quite well. | Didn't care for the oscillatory characteristics in pitch and roll and it seemed that speed stability and the gust excited oscillations and then would have to damp them. Pitch and roll were still controllable and low drag helped during the hovering and the turn. |
| | | B-MB | 0.524 0.315 | 7 | Selected to control the gusts and also the oscillatory attitude characteristics. | Very difficult. Was constantly seeing in both pitch and roll, trying to keep approximate desired velocity. Couldn't perform this task precisely or in any reasonable time. | Very difficult to stop at desired point and get into some large, oscillatory attitudes. | Again attitude was in constant oscillating motion. Could remain close to the hover but really was "jockeying" attitude back and forth. Did use wing tilt a little bit, wasn't really critical. | Couldn't really stay over hover point consistently, however, lower performance not too bad compared to other subjects. Did manage to land it. Lot of control activity in both hover and landing. Definitely some interaction between roll and pitch. | Objectable features were the oscillatory nature of attitude and response to turbulence. Really had to watch the oscillatory attitude characteristics which were difficult to damp. |
| 1112 | NC $T_0 = T_A = 0.6$ | A-FB | 0.587 0.393 | 8 | Set in attempt to maintain attitude stability. | Air taxi very difficult because of difficulty in holding attitude precisely. No problem in initiating aircraft motion as drag seemed relatively low. Some difficulty holding precision hover at the end of maneuvers. Excessive attitude changes often took place due to inability to control attitude. Control deflections were quite large and at times developed PIO-type oscillations. | Hover somewhat difficult due to the very poor attitude control. | Required very little wing tilt compensation for mean wind. Most concentration was on maintaining attitude stability. Height control suffered somewhat because of the high workload in pitch and roll. | Hover somewhat difficult because couldn't control attitude accurately. Control activity was large. | Most objectionable feature was inability to control roll and pitch attitude due to the dynamics being oscillatory, lightly damped, and influenced by control lags. That performance generally quite poor. Considerable compensation required just to maintain control at times. |
| | | B-FB | 0.414 0.274 | 8 | Selected to control gusts and to some extent counteract effects of control lags. | Could just perform the maneuvering task. Was in constant oscillation in both pitch and roll. By control input built up an oscillation which required considerable effort to damp. Difficult to stabilize and hold desired velocity and to stop precisely and hover. Some large attitude excursions occurred. | Same problem as with air taxi. Could stop the aircraft but large attitude excursions occurred. | Managed to retain hover position while turning but attitude went into wild oscillations and just about lost control. Developed one extended PIO in pitch. By stopping, control inputs was able to gain control. | Could hover but not as precisely as desired. Attitude oscillations made it difficult. Did manage to land, but it was tough. Lateral dynamics definitely affected longitudinal dynamics and vice-versa. | The attitude characteristics in both roll and pitch are very objectionable. Roll and pitch in constant motion through large angles. |
| | | B-MB | 0.345 0.310 | 10 | | | | | | Uncontrollable. Tried lifting off and hovering. Couldn't remain stationary for more than 5 or 10 sec without developing a PIO. Couldn't start to pitch the would couple in some lateral motion. Tried 4" or seven different times, but just couldn't keep attitude under control. |
| 1113 | NC $T_0 = T_A = 0.1$ | B-FB | 0.433 0.345 | 4 | Selected to give response desired in pitch and roll and also to counteract the effects of turbulence. | Could perform this maneuver fairly well although did have to constantly attenuate most effects to roll, resolved attitude angle high drag helps the maneuvering task. Able to stabilize fairly well desired velocities. | No great problem. The high drag helps, made have to watch attitude response to turbulence, but attitude seems to be relatively predictable. | Performance fairly good. Significant amount of attention required to attenuate gusts. | Hover performed fairly well. Significant amount of attention required to attenuate gusts. Can land fairly well too. | Primary objective is the response to turbulence in pitch. Attitude seemed fairly predictable. Large drag helped in maneuvering and quick stops. |

TABLE B-II (Continued)

| Case | Conf. Parameters | Pilot, Sim. mode | $\frac{V_a}{V_b}$ | FR | Pilot Comments | | | | |
|------|-------------------|------------------|-------------------|-----|--|--|---|--|--|
| | | | | | Selection of Control-I Qualification | Maneuvering | Take-Off | Turn-Over-After | Overall Pilot's |
| 111A | $V_a = V_b = 0.3$ | A-7B | 0.310 0.275 | 5.5 | Selected for adequate control of the oscillatory attitude dynamics. | Minor large attitude changes required to achieve control but could stop with great deal of precision and could have fairly well control for being blown around in positive oscillations. | Developed problem was lack of tilt control. Could stop quite easily at desired point. | Not blown around quite a lot, but we were confident this wing tilt control with anticipation is attempt to maintain hovering position. | Most objectionable feature was lack of attitude response to gusts. Large attitude lag in response to gusts but at times to steady FTD. |
| | | B-7B | 0.377 0.257 | 3 | Selected primarily to get attitude under control and to control attitude in presence of oscillations (which were not too difficult to control). | Response to control inputs was very poor. Also to initiate motion and stabilize and hold. Control oscillatory character was difficult to control. | Generally could come to the stop fairly accurately and hold lower without too much difficulty. High drag apparently helped. Blown off a little when trying to come to a desired position. | Turn-over did not seem to be very difficult if it were during had been available. Rapid wing tilt rate has improved things considerably. | Objectable features - slightly oscillatory characteristics in roll and pitch. Some features - high drag helped during the recovery and quick stop. |
| | | B-8B | 0.380 0.380 | 7 | Selected to control turbulence and also effects of speed stability during the maneuver. | Could perform the task, but very difficult and not very precisely. Very difficult to control attitude and periodically would develop slow FTD, especially L. roll. | Difficult to smoothly transition control gain; position. Sometimes got into fairly large attitudes. Poor performance. | Difficult. Got my off to lower position a couple of times. Constantly rolling and pitching and walling back and forth. Never really stabilized attitude. Used considerable wing tilt control. | Attitude control very objectionable. Large response to gusts. Large speed stability effects when maneuvering and very oscillatory. Very difficult to stabilize once an oscillation started. Had to be very careful about trying to stabilize attitude due to apparent lag effects. |
| 111B | $V_a = V_b = 0.6$ | B-7B | 0.334 0.377 | 6 | Selected to control large oscillations which result in pitch and roll. | Response to control inputs is very poor. Large oscillations result that made a very great deal of compensation to be able to perform the task at all. Can't perform the task precisely or stabilize and hold velocities. Significant response to turbulence. | Can be performed. Large attitude changes as it does in maneuvering, but still with a difficult task to perform. | Very, very difficult to perform. Tried to develop large attitudes and at one point was in an uncontrolled FTD, just managed to regain control. | Oscillatory character. Little very objectionable in pitch and roll along with inability to gain "new. Sometimes had to grab hold of the stick and hang on or only was able to retain control. Almost lost control once. |
| 111C | $V_a = V_b = 0.1$ | B-7B | 0.407 0.351 | 6 | Selected primarily to control aircraft response to turbulence and to compensate for the lack of damping and effects of speed stability in recovery and quick stop. | Response to control inputs was not particularly good. Large attitude oscillations resulted when attempting to maintain velocity. Missed desired stopping points several times due to the effects of the speed stability, turbulence, and gusts. Attitude control was a problem. | Could stop fairly quickly but attitude control was a problem. | Wasn't particularly difficult to maintain over the spot because of the low drag. However, attitude control was a problem. While diverting attention to wing tilt indicator sometimes got into very large attitudes. Heads were aching. | Objectable feature was lack of attitude damping. Was to be very conscious of the attitude response to turbulence and recovery to control inputs. |
| | | B-8B | 0.377 0.377 | 5 | Selected to control attitude and turbulence. | Performed maneuver pretty well, but prefer to have more damping. Difficult to maintain the desired velocities, have to watch attitude fairly closely and attenuate the response to turbulence. | Could perform task fairly well. Could certainly stop quickly enough. Developed some attitude angles a little larger than desired but could perform the task fairly well. | Developed over the spot quite well. Low drag helped. Didn't use wing tilt control too much. | The objectable feature was low level of damping in attitude. Really needed some more and moderate response to turbulence. More pilot control activity required than is acceptable or satisfactory. |
| 111D | $V_a = V_b = 0.3$ | A-7B | 0.436 0.443 | 9 | Selected to maintain attitude control to prevent FTD situations. | Using air test attitude control very difficult and consistently got into FTD situations. Had to anticipate desired stopping point. Very difficult to come to precise hover. Descriptive attitude changes caused by gusts. Control deflections rather high frequency and large amplitude. | Difficult because rapid attitude control required FTD situations in both pitch and roll at times. | Was difficult part of this was to maintain attitude control. Position control difficult only because of poor attitude control. | Not objectionable features were response to turbulence and unpredictable response to control inputs seemingly related to control lag and slightly damped dynamics. |
| | | B-7B | 0.441 0.365 | 7 | Selected to control response to turbulence and also effects of speed stability when maneuvering. | Could perform maneuver but require high concentration and constant concern with attitude. Difficulty and more damping or less lag, probably both. Quite difficult to hold attitude. | Difficult. Could stop and in an emergency very perform task, but just didn't have desired attitude control. | Had to be attitude when attention diverted. Difficult time controlling all the degrees of freedom. Also, lack of attitude control tended to cause large displacement in hover position. | Objectable features - lack of damping, large speed stability, oscillatory characteristics in attitude and lag in attitude response. |
| | | B-8B | 0.443 0.375 | 7 | Selected to control attitude oscillations and also attitude response to turbulence. | Difficult to achieve maneuver precisely. Difficult to set the desired attitude in the presence of low damping and effects of turbulence. Couldn't recover smoothly and stop precisely. | Also difficult because of difficulty in holding desired attitude. | Performed this maneuver fairly well, but a lot of control activity was required and showed large attitude oscillations. Managed to land alright but again a lot of work involved. Didn't perform the task adequately. | Objectable features - large attitude oscillations, lightly damped attitude characteristics, large attitude response to turbulence and some oscillations in attitude. |

TABLE B-II (Continued)

| | | | | | Pilot Comments | | | | | |
|------|--|------------------------|-----|----|---|---|--|---|--|--|
| No. | Pilot Remarks | Time | Alt | SR | Selection of Control Sensitivity | Performance | Quick Stop | Turn-Over-a-Spot | Positioning, Vertical Landing, Secondary Drains | Overall Evaluation |
| 1218 | 23 $\phi = \phi_0 + \phi_1$ 3.5 | 4.1 0.565 0.608 | 17 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Air test however very difficult because it was extremely difficult to stabilize attitude. When attitude was directed from display one immediately responded pitch and roll would be used by a pilot. Correcting these large attitudes difficult due to motion lag and poorly damped dynamics. Very difficult to stop within ground track of the air test and control difficulties were extremely large. | Very difficult to control due to poor pitch and roll control. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Most objectionable feature was highly damped attitude response in combination with seat seemed like fairly large control lags. In command is necessary, it has very noticeable. Some ground track errors that control could be lost. |
| | | 3.18 0.402 0.459 | 7 | | Selected to control oscillatory characteristics and response to turbulence. | Response to control inputs fairly good. Large oscillations and a significant response to turbulence make a small amount difficult. Not able to stabilize velocity as well as desired. Ability to stop quickly affected somewhat. Low drag and oscillatory attitude characteristics make precision performance of task difficult. | On stop quickly and don't care for attitude characteristics. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | The objectionable feature was lack of damping and oscillatory characteristics in pitch and roll. At no time could be lost control. |
| 1219 | 24 $\phi = \phi_0 + \phi_1$ 0.30 $\phi = \phi_0 + \phi_1$ 3.33 | 4.1 0.565 0.608 | 7 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Very difficult to perform with any precision. Attitude response to control inputs very, very difficult. Attitude (especially pitch) is almost constant motion. Temporary to develop 20° in lateral control. Only way could roll attitude under control was to perform "roll" take land off track and let pitch damp itself. Couldn't perform air test well because of difficulty with attitude. | Difficult to perform because of poor attitude characteristics. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Attitude characteristics very objectionable. Over damp and oscillations except to hold pitch level. At such control over this case. |
| 1220 | 25 $\phi = \phi_0 + \phi_1$ 0.30 $\phi = \phi_0 + \phi_1$ 3.33 | 4.1 0.565 0.608 | 10 | | Selected to control oscillatory characteristics in an attempt to stabilize pitch and roll attitude. | Control was almost dead off or very, very small lags. However response attempted to the control input up large violent oscillations. | | | | Don't control this because of inability to suppress attitude oscillations. |
| 1221 | 26 $\phi = \phi_0 + \phi_1$ 0.30 $\phi = \phi_0 + \phi_1$ 3.33 | 4.1 0.565 0.608 | 4 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Could perform task fairly well. Noticed somewhat twisting oscillations in pitch and roll that had a tendency to sustain themselves, although low level and fairly quickly damped. | Could stop quickly and precisely, the lag was somewhat annoying when attempting to roll out after the quick stop. | Could perform task fairly well. Noticed somewhat twisting oscillations in pitch and roll that had a tendency to sustain themselves, although low level and fairly quickly damped. | Could perform task fairly well. Noticed somewhat twisting oscillations in pitch and roll that had a tendency to sustain themselves, although low level and fairly quickly damped. | Objectable feature was roll oscillations on initiation in pitch and roll which was somewhat irritating. Generally well damped, could control attitude fairly well. |
| 1222 | 27 $\phi = \phi_0 + \phi_1$ 0.30 $\phi = \phi_0 + \phi_1$ 3.33 | 4.1 0.565 0.608 | 3 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Could perform task pretty precisely. Noticed the effects of gusts a little but it wasn't difficult. Could stabilize and hold velocity. Response to control inputs quite predictable. Nicely damped. | Re problem staying precisely and controlling attitude. | Could remain over the spot quite well. That fairly easy to perform using wing tilt control during the turn. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Attitude control very, very good. Effectively damped, easy to control, very predictable and stable. |
| 1223 | 28 $\phi = \phi_0 + \phi_1$ 0.30 $\phi = \phi_0 + \phi_1$ 3.33 | 4.1 0.565 0.608 | 2 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Response to control inputs quite predictably, well damped. Very steady and noticed very few oscillations. Could stabilize and hold velocity. Response to control inputs quite predictable. Nicely damped. | Not difficult. | Could remain over a spot very well. Attitude nicely damped, no problem with pitch and roll and no problem stopping on preselected headings. Used a small wing tilt. Wing tilt changes were not large. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Attitude control very, very good. Effectively damped, easy to control, very predictable and stable. |
| | | 4.10 0.300 0.355 | 3 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Easy to perform. Easy to select desired velocity and hold it. Can stop precisely. No problem. | Performed the task quite precisely. Very positive attitude response to control inputs. No noticeable lags. | Could perform quite precisely and remain over spot. Wing tilt control although not critical, was coordinated with with attitude relative to the turn rate. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Favorable feature in command good, well-damped, positive pitch response and roll response. |
| 1224 | 29 $\phi = \phi_0 + \phi_1$ 0.30 $\phi = \phi_0 + \phi_1$ 3.33 | 4.1 0.565 0.608 | 3 | | Selected to control attitude in an attempt to stabilize pitch and roll attitude. | Roll wasn't particularly difficult but did notice the effects of lags in response to control inputs. Had to be careful about making control inputs. Had to anticipate change in attitude a little more than would have to without a lag. However, could perform task fairly well. | Sometimes vibration positive a little bit. Some oscillations in position resulted because didn't get attitude reversed quickly enough. | Could do this fairly well, no real problems. Coordinated wing-tilt control with different parts of the turn relative to turn rate. | Roll attitude was directed to stabilizing pitch and roll. For this reason control of both attitude was directed the very poor due to the high pilot workload. One very little wing tilt control. | Found the lag in roll and pitch to be an objectionable feature, but really serious but it did result in performing the task less precisely than had previously. |

TABLE B-II (Concluded)

| Case | Task | Altitude | Rate | Pitch | Roll | MIP Commands | | | | | |
|------|--|----------|----------------|-------|------|--|---|---|--|--|---|
| | | | | | | To achieve of control requirements | Interacting | Quick Chase | Turn-Over-Adjust | Pre-land with Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 1129 | 62 $\dot{\theta}_0 = 0.1$ $\dot{\phi}_0 = 0.1$ $\dot{\psi}_0 = 0$ | 6.75 | 0.122 0.299 | 5 | 5 | Selected in an attempt to gain control of pitch and roll oscillations. | Could not perform recovery particularly well because of constant roll oscillations. Some oscillations in pitch, but roll was most disturbing. | Difficult to perform task with any precision because of constant roll oscillation. Really large angles (10 deg or more), constant oscillations and relatively high frequency. | Same close to losing roll control during maneuver. Couldn't do it particularly well because of roll. Jing that control cost a little. | Could stabilize aircraft in some fairly well, but couldn't move precisely. Could manage to land it but not with precision. Definitely some interaction between pitch and roll. | Roll and pitch oscillations very objectionable, unacceptable. |
| 1130 | 62 $\dot{\theta}_0 = 0.1$ | 6.75 | 0.122 0.299 | 5 | 5 | Selected to gain control of pitch response to turbulence and cross-stability effects etc. maneuvering. | Not too difficult to perform. Had to pay close attention to attitude. It was disturbed by turbulence, but fairly controllable. Could stabilize and hold the velocity and stop precisely at the times fairly well. | When a real problem, could perform task fairly well but had to watch attitude as it was quite responsive to turbulence. | Could perform as well as attitude, but remained over the next fairly well. Only a little wing tilt control used as wing apparently small. | Wid practice without too much difficulty. Although was fairly active with control stick. Vertical landing no problem. | Objectable features were the attitude response to turbulence and relatively low heading. However, attitude was reasonably predictable but required a good deal of attention and control activity. |
| | | 6.75 | 0.122 0.299 | 5 | 5 | Selected to gain control of attitude oscillations and attitude response to turbulence. | Could perform these maneuvers fairly well, but attitude response to turbulence was slow in the attitude response, was coming. Had to watch attitude fairly closely to perform the maneuver well. | Had to be somewhat cautious in performing this task because didn't want to make too large an attitude change. | Performed the fairly well, but couldn't hold position quite as well as desired. Found the wing tilt control to correct for some wind effects. | Performed better quite well. Vertical landing not too difficult, managed to do it fairly well. Only a little interaction between dynamics. | Objectable features are lack of adequate attitude warning and attitude response to turbulence. Attitude was controllable but required some effort. |
| 1127 | 62 $\dot{\theta}_0 = 0.1$ $\dot{\phi}_0 = 0.1$ $\dot{\psi}_0 = 0$ | 6.75 | 0.122 0.299 | 5 | 5 | Selected to gain control of oscillations in attitude. | Response to control inputs undesirable. Roll and pitch in almost constant oscillation of fairly large amplitude. Almost impossible to stop. Could stop fairly well, but difficult to maintain velocity. | Lot of attitude action, difficult or impossible to damp large amplitudes. Affected ability to stop at desired lower position. | Again large oscillations, especially in pitch. Constantly overruling it and occasionally would get a large oscillation in roll too. Very disagreeable. Not too concentrate as much on attitude that it took not concentrate away from covering position. | Could move fairly precisely, but fairly large, constant motion attitude oscillations. Could land it alright. Some interaction between roll and pitch due to the oscillatory nature of the dynamics. | Pitch oscillations in pitch and roll very objectionable, very undesirable. No evidence of lack of control power. |
| 1128 | 62 $\dot{\theta}_0 = 0.1$ | 6.75 | 0.122 0.299 | 5 | 5 | Selected in an attempt to get attitude under control. | Very difficult to perform. Couldn't perform this very well. Difficult to observe attitude, very noisy and then had to build up attitude oscillations which are rising. | Couldn't really perform a quick stop for loss of losing attitude control. | Did this very slowly and performed the task fairly well, but attitude was in constant oscillation. Needed wing tilt control to help perform the task. | Not too bad, but had to be careful not to make large loads for time of setting, everything into oscillation again. Can perform the vertical landing, initiate interaction between roll and pitch dynamics. | Objectable features include lack of damping very oscillatory lightly damped responses in pitch and roll. Very responsive to turbulence. |

*As per data, after
pitch control and roll
inputs

TABLE B-III

PILOT COMMENTS FROM THE STUDY OF PITCH, ROLL AND YAW CONTROL MOMENT LIMITS
Flying Qualities Results Given in Table A-IV

| Case | Conf. Parameters | Pitch Mode | Roll Mode | Yaw Mode | Pilot Comments | | | | |
|------|---|------------|-----------|----------|--|---|---|---|---|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precedence of Vertical Landing, Secondary Functions |
| L-10 | N-1 $K_{\phi} = 0.360$ $K_{\psi} = 0.315$ $K_{\theta} = 0.120$ | A-79 | 0.301 | 7 | Selected to get attitude response desired. | Good response to control inputs in pitch and roll generally, however, when maneuvering forward tended to run out of control power occasionally and would pitch so that it was somewhat difficult to stabilize. However, in general could perform test fairly well. | Disagreed with quick stop developed a brief oscillation due to lack of control power but managed to recover fairly quickly. | Could perform over spot quite well, no difficulty. Well damped configuration. | No problem. Could maneuver precisely, sufficient control power. Vertical landing alright as well. |
| | | | | | Selected to get the desired attitude response. | Generally could perform with fairly well. Didn't have any great difficulty in stabilizing velocity and stopping reasonably precisely. During the X maneuver was disturbed by a gust and couldn't control it due to lack of control power. | Generally no problem. Didn't notice any lack of control power but had previously during the X maneuver. | Could perform this fairly well but noted that it lacked a little control power to control roll and pitch. That using tilt controls a little. | Could lower fairly precisely without too much vertical. Vertical landing was no problem. |
| L-10 | N-1 $K_{\phi} = 0.296$ $K_{\psi} = 0.157$ $K_{\theta} = 0.132$ | A-79 | 0.301 | 3 | Not to achieve desired attitude response for maneuvering as there were very little gust effects noticeable. | Maneuvering performance was very good and required very little pilot compensation and very little compensation. Control deflections generally very small and low frequency. | Could perform quite well although a small amount of compensation required to stop at desired point. Noticed very slight limitation of control power, but this occurred only on a very abrupt control input. | Quite okay, required very little pilot effort and very little thrust tilt trim control. | Down performance was very good and very little pilot effort required. |
| | | | | | Selected to get the attitude response required. | In general this wasn't a particularly difficult task to perform, however once or twice noticed a lack of control power. In two instances attitude pitched up and couldn't do anything to control it until the gust had passed. Limited in control power at an insufficient level. | Didn't have any problems. | Could perform this maneuver quite well remaining over spot very precisely that only small amount of wing tilt. | Could lower quite precisely. Vertical landing no problem. Moderate to low amount of control activity being however vertical landing. |
| | | | | | Selected to get desired attitude response. | No problem performing task. Could initiate and hold velocities and stop precisely. No excessive attitude changes involved. | Could perform this task precisely. | Could do this accurately and rapidly. Didn't have to use wing tilt control too much. | Down to have a little bit of trouble holding lateral hovering position but it seemed this task wasn't particularly difficult. Vertical landing not much of a problem. |
| L-10 | N-1 $K_{\phi} = 0.432$ $K_{\psi} = 0.306$ $K_{\theta} = 0.134$ | A-79 | 0.296 | 2 | Not to achieve desired attitude control for maneuvering. | Air taxi performance was very good with very little pilot compensation and effort required. Control deflections small and generally low in frequency. | Could perform quite well and there was no indication of a limitation on control power. | Performance was good with little pilot effort required. Very little thrust tilt trim control required to perform turn maneuver. | Down performance very good with a minimum of pilot effort required. |
| | | | | | Selected to get control of attitude and attitude response desired. | Could perform maneuver quite accurately, initiate all desired velocities with no problems. No obvious lack of control power. Topped very easy to control. | No evident lack of control power anywhere. Could perform maneuver and stop precisely. Did not develop any large attitude angles due to lack of control. | No problem performing maneuver. Did it quite accurately, didn't have to rely on wing tilt control too much. | Could lower fairly precisely, but with a little difficulty. Vertical landing no problem. Moderate to small amount of control activity. |
| L-10 | N-1 $K_{\phi} = 0.299$ $K_{\psi} = 0.315$ $K_{\theta} = 0.120$ | A-79 | 0.317 | 3 | Selected to get desired attitude response. | Not difficult at all to perform this maneuver. Could do it quite precisely, could initiate and stabilize velocities without any problems and stop precisely without large attitude angles. | Generally had no problem but when performing the roll quick stop once noticed a lack of control power. | No problem, performed this task precisely. Did use wing tilt control a little but wasn't really essential. | Could lower quite precisely without great deal of activity. Vertical landing no problem. |
| | | | | | Selected to get response desired to attitude. | No problem. Very predictable response, could hold attitude quite well. Slight tendency to drift off just desired hovering point but that was fairly easily controlled. | No problem, could perform these quite well stop very quickly and hold position after the stop without any problems. | Could maneuver quite accurately and use fairly released, no great difficulty. Wing tilt control used only a little during turn. | Could remain over hover point without any problem and didn't have to use too much control activity. Vertical landing not difficult either. |
| L-10 | N-1 $K_{\phi} = 0.370$ $K_{\psi} = 0.280$ $K_{\theta} = 0.120$ | A-79 | 0.300 | 7 | Selected to get the response desired in pitch and roll and also in an attempt to recover control power deficiency. | Would like to see a little more control power as it had some effect on ability to perform the task even when gusts were low. On one instance when maneuvering longitudinally got hit with a gust and just lost control of pitch for several seconds. This degraded task performance. | Was alright, didn't get combination of effects that caused loss of control, but would like to see more control power. Performance lacked precision. | Down more control power, did use wing tilt a good deal during this task. | Down alright. Manage to land vertically also. |
| L-10 | N-1 $K_{\phi} = 0.370$ $K_{\psi} = 0.370$ $K_{\theta} = 0.150$ | A-79 | 0.350 | 3 | | Response to control inputs during air taxi very predictable in both pitch and roll. Required somewhat large attitude changes to initiate pitch during maneuvering but could stop very easily at desired point. Attitude changes not objectionable because of good attitude control. Would like to see hold hold landing and attitude fairly well. | Required large attitude changes. Only disagreement was slight fluctuation in control power just after stop but this was only slightly annoying and caused no degradation in performance. | Required somewhat large changes in wing tilt angle in order to hold hovering position but performance was relatively good because of good pitch and roll control. | Down required very little control activity. Most objectionable feature was gust disturbance in the longitudinal and lateral position of the aircraft. |

TABLE B-III (Continued)

| Case | Cof. of Architecture | Pilot-Flt. Mode | $\frac{d_{eff}}{d_{ref}}$ | PR | Pilot's Comments | | | | | |
|------|--|-----------------|---------------------------|-----|---|---|--|---|--|--|
| | | | | | Selection of Control Sensitivity | Maneuvering | Quick Steps | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 146 | RC $K_{RC} = 0.380$ $K_{RC} = 0.360$ $K_{RC} = 0.150$ | B-MB | 0.297 0.218 | 2.5 | Selected to get attitude response desired. | No great difficulty, did notice that when maneuvering laterally tended to get them off in longitudinal position occasionally. Could correct for it fairly easily. | No difficulty. Could stop quite precisely and remain over spot. Added some more maneuvering and quick stopping somewhat easier. | Could perform this fairly accurately but had to watch carefully wing tilt position relative to heading. Used caution while wing tilt to perform task precisely. | Never no problem, could perform fairly well. Vertical Landing not difficult. | No real objectionable features, might be desirable to have somewhat lower drag, but could correct for most effects of drag. No real evidence of a lack of control power. |
| 147 | RC $K_{RC} = 0.466$ $K_{RC} = 0.140$ $K_{RC} = 0.182$ | A-FB | 0.270 0.233 | 3 | Set to gain adequate pitch and roll response during air taxi maneuver. | Air taxi relatively easy and performance good. More attitude control was good but no problem holding heading or altitude. Control deflections relatively small and low frequency. | During rapid attitude changes seemed to notice a slight deficiency in control power. No effort on performance but it did seem to take a little more roll and pitch slightly oscillatory. | Control easily maintained, no serious effect on work. Wing tilt was very small. | Maneuvering, landing and takeoff done with little effort and relatively good precision. | Only minor replacement deficiency was apparent correction of pitch and roll control during very rapid large attitude changes during the quick stop maneuver. |
| 148 | RC $K_{RC} = 0.800$ $K_{RC} = 0.605$ $K_{RC} = 0.175$ | A-FB | 0.260 0.194 | 6 | Set to gain adequate roll and pitch attitude control for the maneuver task. | Good attitude control but did notice control power deficiencies during air taxi. Control deflections relatively low in amplitude and frequency. | Indicated control power to do a good quick stop. Tended to use some wing tilt to assist in longitudinal quick stop maneuver. | Had some difficulty maintaining position during turn due to the same wing effects. | Never, landing and takeoff no difficulty. | Good effects were minimal. The most objectionable feature was inadequate control power for rapid maneuvering during turn maneuver. This prohibited rapid and precise maneuvering with the speed desired. |
| | | B-FB | 0.513 0.399 | 8 | Selected to attempt to control pitch and roll attitude during gusts. | Difficult to hold maneuvering speed accurately. Pretty much at the whim of the gusts when they got too large. Had to wait till they subsided and then attempt to continue. Couldn't perform task precisely. | Precision directly dependent on level of the gusts that happen to be present at any given time. | Lost control once, began to develop a roll attitude when the gust hit, gave such a large roll attitude had to really make an effort to retain control. | Never wasn't too bad but every now and then got rocked with a gust and had to ride with it. Wing tilt control used fairly heavily to hold heading position. | Control power inadequate when hit by a large gust, then the gusts were small configurations seemed to be relatively good but with large gusts difficult to retain control. |
| 149 | RC $K_{RC} = 0.908$ $K_{RC} = 0.661$ $K_{RC} = 0.173$ | A-FB | 0.213 0.264 | 8 | Set to ensure adequate attitude control in pitch and roll. | Not too much difficulty encountered in air taxi as long as speeds kept relatively low and small attitudes used. Attitude control required some compensation although gust disturbances were rather minor. | Presented some difficulty in that occasionally got hit by a gust while trying to maneuver rapidly and momentarily couldn't control attitude too well, although did not lose control. | Had to be done with rather gentle maneuvers and even had difficulty bringing out some wind due to inadequate control power. Small amount of wing tilt required. | Never was a problem, neither was landing or taking off. Control activity was rather low. | Most objectionable feature was limitation on control power in pitch, roll or yaw limitation did not seem to present any problem. Control capability occasionally in question. High pilot concentration required. Must be flown with small amplitude maneuvers. |
| | | B-FB | 0.530 0.404 | 4.5 | Selected to control turbulence and speed stability. | In general could perform task fairly well. Every now and then hit with a large gust that disturbed attitude, but was always able to maintain control. | In general could perform task fairly well, but occasionally hit with a large gust that could prevent smooth performance of task. | Performance fairly good, used wing tilt control a good deal. | No problem hovering, adequate control power. Apparently control power only inadequate when not ground speed, some wind, and turbulence components were large. | Objectable feature was deficiency in control power. In general configurations seemed to be fairly well damped. Response to turbulence wasn't that large, fairly low frequency. |
| 150 | RC $K_{RC} = 0.986$ $K_{RC} = 0.777$ $K_{RC} = 0.211$ | A-FB | 0.304 0.261 | 4.5 | Attitude control well damped and gust effects minimal. Maneuvering performance is good although relatively large attitude changes required to maneuver. | Attitude control well damped and gust effects minimal. Maneuvering performance is good although relatively large attitude changes required to maneuver. | Retained control power limitation when making rapid attitude changes although it does not seem to impair performance. | Relatively easy except that large amounts of wing tilt are required to offset some wind effects. | Never performance is relatively good and control power seems adequate. | Most objectionable features are the gust effects on aircraft position and the noticeable limitation of control power during rapid attitude changes. |
| | | B-FB | 0.531 0.424 | 3 | Selected to control turbulence and speed stability when maneuvering. | Not difficult. Could maneuver precisely and hold attitude quite well and generally had no problem performing task. Noticed just once some minor deficiency in control power but maybe it was just a large gust. | Could stop precisely and hold desired roll attitude quite well. Didn't notice any lack of control power. | Performed this quite well. Didn't notice any lack of control power. Did use wing tilt a good deal during the turn. | Could hover precisely. Could also land quite well without any real difficulty. | No real objectionable features, some slight response to turbulence noted but not too bad. Dynamics are quite well damped and workload relatively low. |
| | | B-MB | 0.426 0.348 | 5 | Selected to control effects of turbulence acting through speed stability actively, allow to control effects of speed stability while maneuvering. | Modestly difficult to perform. Had to attenuate effects of turbulence on pitch and roll. Affected ability to stop precisely to some extent, but could perform the task fairly well. | Didn't get into any maneuvering attitudes and performance relatively good. | Was difficult, couldn't hold hovering attitude particularly well and did develop some fairly large attitude changes. Lot of roll and pitching motion. Used wing tilt control a great deal. | Could hover precisely but it involved fairly large attitude changes and a lot of stick action. Vertical Landing alright. Some interference between dynamics, at least during the turn. | The objectionable features were the large response to turbulence in pitch and roll and the lack of damping. Some lack of predictability in the pitch and roll response to stick inputs. Didn't notice any lack of control power, however. |
| 151 | RC $K_{RC} = 1.066$ $K_{RC} = 0.799$ $K_{RC} = 0.229$ | B-MB | 0.426 0.334 | 4.5 | Selected to get desired response and also to overcome effects of turbulence. | In general could perform this maneuver without any difficulty. Had to attenuate the effects of turbulence, however. | Could stop precisely and rapidly without excessive attitude but had to watch the effects of turbulence. | Also could perform this maneuver fairly precisely but again turbulence was significant. Didn't notice any lack of control power in all these maneuvers, however did have to use wing tilt control a good deal in turn because of some wind. | Required a fair amount of activity as did vertical Landing. Had to attenuate the effects of turbulence. | Response to turbulence was somewhat too large. However, in general attitude was predictable in response to control inputs. |

TABLE B-III (Continued)

| Case | Alt. Parameters | Altitude, ft. | H_{θ} , ft./sec. | H_{ϕ} , ft./sec. | Pilot Comments | Selection of Control Authority | Maneuvering | Quick Stops | Turn-Over-As-Yet | Vertical Motion, Vertical Landing, Secondary Dynamics | Overall Evaluation |
|------|---|---------------|-------------------------|-----------------------|----------------|--|--|---|---|--|--|
| | | | | | | | | | | | |
| 1002 | NO $H_{\theta} = 0.850$ $H_{\phi} = 0.750$ $H_{\psi} = 0.170$ | A-78 | 0.257 | 0.331 | 1 | Selected to control attitude response to turbulence and also attitude changes when maneuvering. | Don't think I could perform this well. There were times when hit by turbulence and would almost come to a stop. Seemed to find attitude somewhat erratic quite a lot. Large attitude changes did result. | Generally could arrest velocity without too much difficulty. Kind of difficult to hold velocity. Also, on the 1st quit stop was trying to arrest speed but into a large attitude excursion and thought about to lose control. | Attitude control line of attack. Large attitude excursions but could hold heading position fairly well. No problem with directional control of course activity. Could land alright. | Could lower fairly accurately. As long as attitude changes were fairly small didn't get into too much trouble. Fair amount of control activity. Could land alright. | Objectable features were the proximity to velocity control of attitude. Also the large attitude excursions and thought that control might be lost. They think the attitude response seemed to be fairly well damped. |
| 1003 | NO $H_{\theta} = 0.979$ $H_{\phi} = 0.885$ $H_{\psi} = 0.107$ | A-78 | 0.215 | 0.138 | 10 | | Inadequate control power, difficult to establish velocities. At times estimated either pitch or roll control. | Inadequate control power, difficult to develop velocities. Force and air action was to be controlled using wing tilt, but control almost inadequate to perform lateral maneuvers. | Lost control once and was unable to recover. Lateral control almost because of turbulence effects. | | Inadequate roll and pitch control moments. For control moments CL. |
| | | | | | | Continuous maneuvering velocities affected by turbulence through pitch and roll. As in general could maneuver fairly well but lack of desired precision. One or twice increased transient water may have been caused by lack of control power. | Could stop fairly quickly and didn't have too much trouble holding maneuvering velocities. | Didn't have too much trouble, but did go through some fairly significant attitude oscillations. (Particularly in roll). Had to use wing tilt a good deal. | Fair amount of control activity required to hold heading. Could land without too much difficulty. Secondary dynamics had some interaction but nothing really severe. | Response to turbulence too large and noticed some lack of control power. For various control input cases of pitch and roll, not able to attenuate error. | |
| 1004 | YES $H_{\theta} = 1.368$ $H_{\phi} = 0.500$ $H_{\psi} = 0.204$ | A-78 | 0.226 | 0.127 | 8 | Set for attitude response for air ball. | Inadequate control power to maneuver very rapidly. Definite deficiency in both roll and pitch. Lateral maneuver was very slow because didn't have lateral thrust trim. | Set possible because initial velocities necessary for quick stops could not be developed. | Required concentration and the wind blew the aircraft quite a lot. Difficult to control because of inadequate control power. Had to make liberal use of wing tilt in an attempt to offset the deficiency in longitudinal control power. | Maneuvering and landing were no particular problem as control power was adequate for these maneuvers. | The most objectionable features were (1) deficiency in control power in pitch and roll when maneuvering and landing over a spot and (2) the gust effects on pitch attitude. It required some pilot attention. Most control carefully during maneuver to avoid losing control of the aircraft. |
| | | | | | | | Generally response to control inputs was acceptable. Could stabilize velocities fairly well and stop without too much difficulty. Attitude kind of responsive to turbulence. Would like a little more damping. | Not too much difficulty. Defined following almost stops there was no tendency to oscillate in pitch or roll. Adequate control power. | Could remain over the spot fairly well but did develop some large attitude changes. Fair amount of attitude damping. Control power was so. Further, wing tilt control used a good deal. | No real problem. Could lower quite precisely although fair amount of control activity required. | A fair amount of attitude response to turbulence and would like to see a little more with some damping. Control power seemed adequate, noticed no large oscillations and no tendency to lose control. |
| | | | | | | | Selected to control attitude response to turbulence and speed stability when maneuvering. | Response to control inputs not quite as predictable as desired. Some like acceleration-type response. Difficult to stabilize velocities and stop precisely. Gust disturbances are overwhelming, very large. | Could stop fairly accurately but it was difficult to do everything precisely. Didn't notice any lack of control power. | Managed to do this without too much difficulty but did develop some fairly significant roll and pitch attitudes. Wing tilt control was used a good deal for some wind effects. | Could hold position pretty well, but was always oscillating back and forth in doing so. Lot of turbulence to overcome when hovering. Vertical landing is inherently difficult. Probably some interaction effect between pitch and roll dynamics. |
| 1005 | NO $H_{\theta} = 1.197$ $H_{\phi} = 0.975$ $H_{\psi} = 0.201$ | A-78 | 0.256 | 0.259 | 7 | | Worked very high during the air taxi. Roll and pitch attitude fairly responsive to gusts. Attitude response to control inputs very lightly damped. Aircraft made some SAG. Considerable gust disturbances in position and fairly large attitude changes required to maneuver. Limitation on control power evident. However, controllability of aircraft not in question. | Difficult to initiate the rapid maneuvers but could be stopped rather quickly. Limitation on control power evident and this prevented the desired control of attitude. | Fairly difficult because of wind effects on the aircraft position. But control was adequate. Fair amount of wing tilt control required to hold position. | Better performance fairly good, however pilot workload fairly high. | Most objectionable features were first the slightly damped, gust sensitive dynamics, and second, the limitation on control power. Considerable pilot compensation required, however, controllability not in question. The lack of control power and the insufficient attitude stabilization is deficiency that must be improved. |
| 1006 | NO $H_{\theta} = 1.090$ $H_{\phi} = 1.036$ $H_{\psi} = 0.230$ | A-78 | 0.260 | 0.338 | 5 | Selected to control attitude response to turbulence and attitude response to maneuvering velocities. | Could perform this task fairly well and initiate and stabilize velocities although it took some attention. Response to turbulence was fairly sharp, abrupt at times. | Could stop quite quickly and relatively precisely. Tended to introduce some fairly substantial and rapid attitude changes. | Performed this fairly well, including holding hover position. Used wing tilt control a good bit. | Fairly high workload when hovering but performance fairly good. Could land. Not too much interaction between dynamics. | Large attitude response to turbulence and the lack of predictability in the attitude response to wind inputs most objectionable features. Needs more damping. |

TABLE B-III (Continued)

| Case | Circ. Parameters | Sim. Mode | $\frac{H_{\text{sim}}}{H_{\text{act}}}$ | FS | Pilot Comments | | | | | |
|------|--|-----------|---|-----|--|---|--|--|---|---|
| | | | | | Selection of Control Sensitivity | Maneuvering | Quick Stops | Turn-Over-a-Spot | Reversion, Vertical Landing, Secondary Landings | Overall Evaluation |
| 1487 | RC $H_{\text{sim}} = 0.246$ $H_{\text{act}} = 0.457$ $H_{\text{sim}} = 0.158$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.239 | 4 | Selected to get desired attitude response, seemed a bit sluggish in attitude. | No real problem. Did notice some slight lack of control power once though, seemed to get a little larger pitch attitude compared than wanted, but in general could maneuver quite well. | Could perform task reasonably well. Not a little difficulty stopping when desired. | Not too difficult. No real hard requirements for wing tilt control. | Little disappointed with ability to hover. Would like to have a little more precision. Vertical landing no problem. | Objector's features include some lack of control power and some apparent effects of lag in attitude control. |
| | | | 0.340 | 4.5 | Selected to get desired response in pitch and roll; seemed to have to increase control sensitivity to overcome lag effects. | Performed quite well, no problem with facilitating and holding desired velocity and didn't get into any particularly large attitudes. | Not really well except once during 1 quick stop; seemed to exceed control power limit. Didn't recover attitude as quickly as desired, although nothing serious. | Performed task fairly well. Little use of wing tilt control. | Couldn't hover quite as precisely as desired. Seemed to keep oscillating away from desired position. Could land alright. | Lag effect seemed to introduce some oscillations and control features were somewhat less precise than desired. Not particularly responsive to turbulence. |
| 1488 | RC $H_{\text{sim}} = 0.332$ $H_{\text{act}} = 0.598$ $H_{\text{sim}} = 0.143$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.233 | 4 | Not for desired attitude response for air taxi. slight overshoot and oscillations about desired attitude following rapid commands. | Air taxi performance relatively good. Slight lag in attitude control required only small increases in concentration to perform taxi. Control collection remains small, even as a little more high-frequency control required to stabilize desired attitude changes. | Performed fairly well, but some overshoot and oscillations about the desired command attitude. | Only small amounts of wing tilt control required. Maneuver was quite easy. | Air taxi performance very good and required very little pilot concentration. Control power seemed to be quite adequate. | The most objectionable feature was the lag in attitude response and then the slight overshoot and oscillation about the command attitude change following rapid control inputs. |
| | | | 0.337 | 4 | Selected to get the response desired in pitch and roll. | Not difficult. Could stop precisely. Could hold velocity without too much difficulty. Minor objection was that pitch and roll seemed to oscillate and that it was slightly difficult to stabilize. | Performance alright and had to damp out oscillations after completing maneuver. | Not difficult. Could perform task fairly precisely, but tended to oscillate somewhat in pitch and roll. | Could hover adequately. Noticed some oscillation, some lack in response, a little bit of unpredictability in control response. Moderate amount of control activity required in hover and vertical landing. | Objector's features were oscillatory nature of pitch and roll after significant attitude change. Could have to follow up to estimate low overshoot. Oscillations seemed fairly well damped, not responsive to turbulence. |
| | | | 0.378 | 3 | Selected to get response desired in pitch and roll. | No problem. Could perform task very nicely. | Also no problem. No lack of damping, the lag did not seem too annoying. | Could perform quite accurately. Didn't use wing tilt control too much. | Some difficulty here, but not too much. Fair amount of control activity required but could hold hover position quite well. | No real objectionable features, some possible lag effects, nothing too bad. Slightly damped, easy to fly. |
| 1489 | RC $H_{\text{sim}} = 0.668$ $H_{\text{act}} = 0.540$ $H_{\text{sim}} = 0.136$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.346 | 2.5 | Selected to get attitude response desired. | Seems to be correct. Inertia acceptable. Seems to be some slight oscillations following control commands, however it was very small. Very slight and of no major significance. Could stabilize and hold desired velocities, stay precisely and hover at the command. | Able to stop precisely and hold position. No large attitude angles. Attitude was quite controllable, except for some slight oscillatory characteristics. | So difficult, didn't seem to rely on wing tilt control too much. | Could hover very precisely with a small amount of control activity. Vertical landing no problem. | No real objectionable features. Possibly features included low vertical and air stable response. |
| 1490 | RC $H_{\text{sim}} = 0.359$ $H_{\text{act}} = 0.457$ $H_{\text{sim}} = 0.128$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.371 | 4.5 | Selected to get desired attitude response. | Noticed some lack of damping and response to turbulence. Every now and then would overshoot attitude command and exhibit some oscillations for lag characteristics in the roll. Could stabilize velocities fairly well, but had problems rolling in and out of maneuvers. | Got into some large attitude angles during 1 quick stop that wasn't easy to damp, settling frequency but it was acceptable. | Could perform maneuver fairly precisely and didn't use wing tilt control much. | Had a little difficulty in holding lateral position. Little more control activity involved and attitude not quite as predictable in hover as would like. Vertical landing no problem. | The oscillatory nature of pitch and roll and the apparent lack of control power to damp made attitude kind of unpredictable. Required a fair amount of compensation in control. It also affected the precision of task performance. |
| 1491 | RC $H_{\text{sim}} = 0.332$ $H_{\text{act}} = 0.598$ $H_{\text{sim}} = 0.143$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.338 | 4 | Selected to get desired attitude response. First of control sensitivity to damp out the oscillations that resulted from lag. | In general could maneuver fairly well. Disturbing report was that attitude tended to oscillate after making a control input, had to make constant attempts to damp it out. This difficulty increased with frequency of maneuver. | Induced attitude oscillations. Could perform task fairly well, some compensation required to damp attitude. | Performed task fairly well, but did get into some moderate oscillations in pitch and roll that affected task performance somewhat. Wing tilt control used a great deal. | Not too difficult to hover, roll released control input required. Vertical landing no difficulty. | Didn't seem for the oscillatory character. Oscillations in pitch and roll. It seemed to affect control capabilities somewhat. Like low g's response; fairly relaxed case. |
| 1492 | RC $H_{\text{sim}} = 0.668$ $H_{\text{act}} = 0.540$ $H_{\text{sim}} = 0.136$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.366 | 3 | Selected to get desired attitude response. | No difficulty. Could perform task very smoothly and precisely. Noticed a little bit of oscillation in roll and pitch but nothing serious. | Could perform task quite precisely. Didn't have any problems rolling and pitching in and out of the quick stops. A little bit of oscillation noticeable, but wasn't difficult to estimate. | So difficult, again noticed some oscillations in pitch and roll but they weren't particularly large and they weren't all that difficult to estimate. Wing tilt control not used much. | Could hover precisely with little control activity. Could land with out difficulty. | No real objectionable features except possibly the slight oscillation in roll and pitch that tended to develop in response to control commands, but it was low level. Slightly damped, low response to turbulence, easy to control. |
| 1493 | RC $H_{\text{sim}} = 0.668$ $H_{\text{act}} = 0.540$ $H_{\text{sim}} = 0.136$ $H_{\text{act}} = 0.1$ $H_{\text{sim}} = 0.1$ | B-79 | 0.366 | 4 | Selected to try to overcome the lack of control power and damping in attitude. | Did this fairly well. Air taxi no problem. Held velocities fairly well and made stop quite precisely. | Did the longitudinal pitch stop alright. In lateral pitch they got into an oscillation which was kind of difficult to damp. | Didn't do this very well. Noticed some large errors in position. Not sure if that was due to the attitude characteristics or due to not paying close attention to it. Did require the wing tilt a good deal. | Generally could do this fairly well. Did get much of around error or better. Still not happy with the attitude response but it wasn't all that bad. Vertical landing OK. Reasonable amount of control activity in the hover and vertical landing. | Not think there is quite as much control error in pitch and roll but in general could perform the task alright. |

TABLE B-III (Concluded)

| Case | Conf. Parameters | Pilot Mode | $\frac{H_{\theta}}{L_{\theta}}$ | FR | Pilot Comments | | | | | |
|------|---|------------|---------------------------------|-----|---|--|--|---|---|--|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Turn-Over-a-Point | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 1484 | RC $H_{\theta} = -0.162$ $L_{\theta} = -0.140$ $H_{\dot{\theta}} = -0.108$ $T_{\theta} = 0.6$ $L_{\dot{\theta}} = 0.1$ | 7-78 | 0.380 0.383 | 3.5 | Selected to get response desired in attitude to overcome damping. | It problem maneuvering, attitude nicely damped and had sufficient control power to perform 1° roll. | Comments as for maneuvering. | Seemed difficult to remain over the spot but that was due to large drag rather than any attitude characteristic. Did perform the task reasonably well though. Wing tilt control was used a good deal, absolutely essential for this configuration. Monitored wing tilt angle a good deal. | Could perform this task fairly well. Noted a slight deficiency in control power which is acceptable. Would like to see a little bit more control power however. Vertical landing OK, moderate amount of control activity involved in hover. | Slightly objectionable feature was a slight deficiency in control power. Good deal of damping, nice response in attitude. |
| 1485 | RC $H_{\theta} = -0.304$ $L_{\theta} = -0.180$ $H_{\dot{\theta}} = -0.199$ $T_{\theta} = 0.6$ $L_{\dot{\theta}} = 0.1$ | 7-78 | 0.333 0.330 | 3 | Selected to overcome the damping and what may have been a lag in attitude response. | Response to control inputs was predictable, well damped. Could develop a smooth consistent velocity and stay precisely. No apparent lack of control power. | Could perform the task quite accurately. No overly acceptable behavior here. | Seemed more difficult because of high drag, but good damping in attitude enabled performance of task fairly well. Did have to use wing tilt a good deal. | Only part of task that had some reservations about. Seemed to be a lag that prevented desired quick response in attitude needed to overcome gusts. Landing performance adequate. Fair amount of control activity involved. | Objectionable feature was apparent lack in attitude response when hovering which degraded performance slightly. Attitude appeared to be well damped. |

TABLE B-IV

PILOT COMMENTS FROM THE STUDY OF INCREMENTAL PITCH CONTROL MOMENTS THROUGH STORED ENERGY

Flying Qualities Results Given in Table A-V

| Case | Def. Parameters | ? Int. Mode | γ_{def} - γ_{def} | P | Pilot Comments | | | | | |
|------|---|-------------|---|-----|---|--|---|---|--|--|
| | | | | | Selection of Control Characteristics | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Functions | Overall Evaluation |
| 151 | NC $H_0 = 0.356$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.05$ | A-7B | 0.275 0.192 | 5 | Selected to get the attitude response needed to overcome the effects of damping. Wide range of control characteristics apparently satisfactory. | No problem laterally, but when diving forward at times lost control of pitch attitude to some extent. It would just begin to rise without control. Also noticed loss of control power when pitching up to arrest forward velocity. | Couldn't really perform an accurate quick stop maneuver. Tended to pitch up and then hang there until attitude came back down again after velocity stopped. | No problem. Wing tilt control used a little to help in the turn. | Hover not difficult. Vertical landing no problem. | Objectable feature was noticeable loss of control power during forward maneuvers and forward quick stops. Other than that it was a good configuration. |
| 152 | NC $H_0 = 0.356$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.12$ | A-7B | 0.350 0.251 | 5 | Set for desired attitude response for maneuvering. | Very small attitude changes required to maintain velocity. Had to anticipate somewhat the desired stopping position but in general the air tank performance was good. Pilot worked low, so had a difficulty holding altitude and heading. | Performed maneuver noticed a slight deficiency in control power, pitch particularly, but at no time lost control of the aircraft nor did it require very much pilot attention to avoid getting into that kind of a situation. | Performance was very good. Worked low and vertically on thrust till trim was required. | Hovering and landing was excellent with very little control activity required. | Overall the most objectionable feature was the slight indication of control power during the quick stop maneuver, but it had very little effect on task performance. |
| | | A-7B | 0.350 0.226 | 5 | Selected to get the attitude response desired. | Good response to control inputs, no problem initiating and stabilizing velocity, possibly only once or twice noticed a small loss of control power when pitching up after moving ahead longitudinally, but these were relatively minor effects. | Performed these with no difficulty and noticed no loss of control power. | Easy to perform. Used wing tilt only slightly. | Not difficult, didn't notice any loss of control power here. Vertical landing not difficult. | Did notice a slight loss of control power once or twice but nothing serious. Will design configuration. |
| 153 | NC $H_0 = 0.356$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.20$ | A-7B | 0.303 0.253 | 5 | Selected to get the attitude response needed to overcome the damping. | Generally could perform task well. Once or twice noticed the nose was pushed up slightly by the gusts while maneuvering. Also, there tended to be some slight pitch-up tendency when arresting velocity, but in general could perform this task fairly well. | Didn't encounter any problems here but was careful when pitching up to stop the motion. | Performed this task quite well with little difficulty. Didn't have to use wing tilt control a great deal. | Hover and vertical landing no problem. Could perform both accurately without much control activity. | Were time when loss of control power noticed. Had to work with inputs somewhat in order to insure that large pitch attitudes weren't developed. |
| | | A-7B | 0.254 0.192 | 4 | Selected to overcome attitude damping and get desired attitude response. | No problem performing task. Noticed some slight change of control power when maneuvering forward and attempting to arrest maneuvering velocity, but generally could perform these maneuvers quite accurately. | Generally no problem, especially laterally. When trying longitudinal quick stops noticed slight deficiency in control power when attempting to arrest forward velocity sharply. | No problem. Wing tilt control was used to a slight extent when turning over the spot. | Precision hover and vertical landing not difficult. No interference among dynamics. | One slight objectionable feature was the noticeable deficiency in control power. That's a real big problem, however. |
| 154 | NC $H_0 = 0.356$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.20$ | A-7B | 0.297 0.251 | 2 | Selected to overcome damping and get the attitude response wanted. | No difficulty, very good. Good attitude response to select and stabilize velocity with no difficulty and stop precisely. | Can stop accurately with no up or down loss of control power. No large attitude motions. | Could perform quite well. But a little to use too much wing tilt. | No problem. Can hover precisely with little control activity. Vertical landing also can be accomplished precisely. Secondary dynamics - No interference. | No objectionable features. Possible feature - predictable attitude response, low response to turbulence. |
| 155 | NC $H_0 = 0.300$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.1$ | A-7B | 0.310 0.295 | 7 | Selected to get desired attitude response. | Difficult to hold longitudinal velocity because of a lack of control power. Attitude control damped, but periods of disturbance damping developed large pitch-up attitude when arresting velocity because of deficient control power. | Difficult to control position and velocity precisely. | At times couldn't position pitch attitude as desired because of the gusts. Had to use wing tilt a great deal, difficult to hold position. | Could generally hover position but blow off once or twice. Not too difficult. Secondary dynamics - No interference. | Objectable features - serious deficiency in control power. |
| 156 | NC $H_0 = 0.350$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.05$ | A-7B | 0.314 0.246 | 5 | Selected to overcome the damping and get desired attitude response. | Could stabilize velocity fairly well, but noticed deficiencies in control power periodically. Had some difficulty controlling pitch attitude, tended to develop large pitch-up angles. | Could perform somewhat fairly well, but had to be careful of pitch. Couldn't make inputs too abrupt. | Could perform fairly well. Didn't have any problems with pitch control. Used wing tilt a good bit. | Noticed a lack of control power. Attitude slightly is responding. | Noticeable deficiency in control power. |
| 157 | NC $H_0 = 0.350$ $\Delta H_0 = 306$ $\gamma_{\text{def}} = 0.1$ | A-7B | 0.347 0.247 | 4.5 | Set to achieve attitude control necessary for maneuvering. | Performed fairly well. Relatively large attitude changes were required to overcome the drag of the aircraft. Occasionally got blown off ground track by gusts. Control moment quite adequate for maneuvering the vehicle. | Required large attitude changes. Noticed control moment deficiency a few times, somewhat could hold or arrest attitude motion. | Required some effort and considerable wing tilt to effect the same wing effects. Control moment was quite adequate. | Performance was quite good, only a low level of pilot effort required. | Attitude dynamics were fairly good. Only problem was that control was periodically deficient. |
| | | A-7B | 0.348 0.225 | 4 | Selected to overcome damping and to get desired attitude response. | No difficulty. Could hold desired velocities and stop precisely. Once or twice attitude got blown off and added the control moment to recover rapidly, not a major problem. | Performed this task precisely, held attitude and velocities without difficulty. | Performed quite well without too much control activity or too great a workload. Used wing tilt a good bit, however. | Precision hover and vertical landing could be accomplished precisely with moderate control activity. | Lack of control power was noticeable. Anyway, but not a major deficiency. In general, the configuration was well designed. |

TABLE B-IV (Concluded)

| Case | C/N | Parameter | Pilot | Altitude | Pitch | Pilot Comments | | | | | |
|------|-----|--|-------|----------|-------|---|---|---|--|---|--|
| | | | | | | Selection of Control Sensitivity | Maneuvering | Quick Stops | Turn-Cover-a-Spot | Precision Landing, Vertical Landing, Secondary Functions | Overall Evaluation |
| 15C | BN | $M_0 = 0.900$ $M_1 = 0$ $M_2 = 0$ | A-1A | 0.375 | 5.5 | Selected to control attitude response to turbulence. | Could perform fairly precisely. Turbulence effects strong, once or twice noticed deficiency in pitch control moment. | Could perform fairly well. Noticed slight deficiency in control power when separating forward velocities. | Difficult to perform. Had to use wing tilt a good bit. Pitch, roll, attitude oscillations fairly large. | Not difficult. Vertical landing OK. No major interaction. | Response to turbulence and slight deficiency in control power during. Predictable attitude response. |
| 15Y | BN | $M_0 = 0.900$ $M_1 = 30\%$ $M_2 = 0$ | A-1A | 0.342 | 5 | Selected to get desired attitude response and rolls to overcome turbulence response. | Could perform fairly well. Noticed slight lack of control power when maneuvering forward. | Could perform fairly well but slight deficiency in control power. | Modestly difficult to perform. Had to select effects of main wing. Like was damping. Used wing tilt control a good bit. | Practically got blown off desired hovering position. Vertical landing to problem. No interaction. | Response to turbulence objectionable, slight deficiency in control power. |
| 15H | BN | $M_0 = 0.900$ $M_1 = 30\%$ $M_2 = 0$ | A-1A | 0.375 | 6 | Set to achieve desired attitude control for maneuvering. | Difficult to maintain large attitudes required to sustain velocity. Noticed no control power deficiency. Could stop fairly readily at desired pitch. Required pilot concentration, and heading and altitude control suffered. | Difficult because of large attitude changes required to start and stop action. Control power inadequate to maintain desired attitude during forward action. | Adequate control power; considerable concentration required because of position disturbances. Considerable wing tilt required. | Performance quite good, good position disturbance damping. | Maneuvering landing, no quick stop objectionable. |
| | | | A-1A | 0.342 | 5 | Selected to continue damping and attitude response to turbulence. | Performed without too much difficulty. Noticed slight deficiency in control power. | Could stop fairly precisely and didn't notice any deficiency in control power. | Modestly difficult due to large drag parameter. Used wing tilt a good deal and had to monitor tilt angle meter closely. | Modestly difficult; developed a use fairly large attitude attempting to hold hover. Could land with no problem, fair amount of control activity. No interaction. | Significant response to turbulence and some deficiency in control power. |
| 15L | BN | $M_0 = 0.900$ $M_1 = 30\%$ $M_2 = 0$ | A-1A | 0.291 | 7 | Set for maneuvering. | Maneuvering force was difficult because of lack of pitch control moment. Could control ground track fairly well but performance very slow because of lack of attitude control. | Difficult to develop desired attitude. Not adequate pitch control moment during rapid attitude changes. | Considerable wing tilt to offset main wing effects. | Hover performance fairly good, control moment seemed adequate. Biggest problem was quite a bit of drag parameter. | Dynamics fairly good. Deflected by lack of pitch control moment, particularly during quick stop. |
| | | | A-1A | 0.241 | 6 | Selected to control turbulence. | No problem performing. Had to counteract effects of turbulence, however. Could stabilize velocity and stop precisely. No noticeable lack of control moment. | Not too difficult. Turbulence affected precision slightly. | Somewhat difficult because of large drag parameters. Pa forced back fairly well; however, had to use wing tilt a good deal. | Precise hover required appreciable control activity and concentration. Vertical landing not too difficult. | Response to turbulence objectionable but attitude fairly well damped. |
| | | | A-1A | 0.342 | 4 | Selected to get desired attitude response to control turbulence effects. | Could perform quite well and didn't notice any lack of control moment. Pitch and roll somewhat responsive to turbulence, but very predictable. | Could perform without too much difficulty. Even when maneuvering forward and pitching to sharply noticed no lack of control moment. | No question of control stability, but had to be sure to remain over spot. Used wing tilt control carefully and coordinated it closely with direction of main wing. | Could perform hover quite well; vertical landing a problem. No interaction. | Only objectionable feature is attitude response to turbulence, but not too bad. |
| 15M | BN | $M_0 = 0.900$ $M_1 = 30\%$ $M_2 = 0$ | A-1A | 0.246 | 9 | Lack of control moment made setting sensitivity meaningless. Used stick as "on-off" controller. | Very difficult, performance poor because of inadequate control moment. Never lost control of aircraft, however. | Couldn't perform because control moment inadequate. | Difficult; large wing-tilt requirements. | Hover performance quite difficult because of inadequate control moment and effects on aircraft position. | Severe deficiency in pitch control moment. |
| | | | A-1A | 0.342 | 6 | Selected to get control over attitude response to turbulence and speed stability effects. | Difficult because had to compensate on attitude and constantly attenuate turbulence effects. | Had to attenuate attitude turbulence response and could hold velocities relatively well and stop abruptly. | Somewhat difficult. Pitch and roll drifted off during turn because of inadequate damping. Used wing-tilt control a good deal. | Hover difficult, but could be performed well with considerable stick activity. Vertical landing could be accomplished but required attention. Some interaction between longitudinal and lateral dynamics. | Large attitude response to turbulence objectionable. Notice lack of control power once or twice. |
| 15N | BN | $M_0 = 0.900$ $M_1 = 30\%$ $M_2 = 0$ | A-1A | 0.246 | 5 | Set to control attitude limitations. | Quite difficult because of gust sensitive and lightly damped attitude dynamics. Pilot worked pitch high. Lack of control moment evident in pitch. Heading and altitude control impaired. | Difficult in longitudinal direction. Failed control moment limitations in pitch. | | Hover performance adequate but required appreciable pilot effort. | Poor attitude characteristics - high gust sensitivity and limitations on control moment. |
| | | | A-1A | 0.342 | 5 | Selected to control attitude response to turbulence. | Could initiate and hold velocities fairly well but constantly attenuated effects of turbulence. | Could stop quite quickly. Had to be aware of turbulence effects. | Could perform quite well, but tendency for pitch and roll attitude to drift off. Wing-tilt control used a great deal. | Could hover reasonably well but fair amount of control activity required. Vertical landing could be accomplished accurately. | Modest attitude damping or reduced response to turbulence. |

TABLE B-V

PILOT COMMENTS FROM THE STUDY OF LONGITUDINAL AND LATERAL INTER-AXIS MOTION COUPLING

Flying Qualities Results Given in Table A-VI

| No. | Task | Pilot | Altitude | Speed | Frequency | Pilot Comments | | | | | |
|-----|---|-------|----------|-------|-----------|--|---|--|---|--|--|
| | | | | | | Selection of Control | Maneuvering | Gain Range | Time-Delay Type | Precision, Power, Control Loading, Secondary Qualities | Overall Evaluation |
| 121 | RC1 $\frac{1}{2} \frac{1}{2}$ $\frac{1}{2} \frac{1}{2}$ | A-7B | 0.30 | 0.30 | 0.30 | Set for desired response for air taxi maneuver | Performance during air taxi was good with a minimum of stick effort. Control deflections were neither too large nor too frequent. | Selected coupling between pitch and roll was very good. This was somewhat surprising and required control correction. | Performance was good and required very little stick time. | Power performance was good with very little control effort required. Control activity was low. | Overall quite good except for some slight attitude changes which were somewhat by cross coupling between pitch and roll axes. Coupling related to the angular rate of the aircraft and to the control input. |
| | | | | | | Selected to get desired attitude rate | Not difficult. Attitude response relaxed, smooth. No coupling evident, but no clear attitude changes in either pitch or roll resulted. | Generally could perform fairly well, however did a bit that was trying to correct roll which seemed to introduce some errors due to attitude coupling. | As difficult. Did not "wing it," control a bit about although it was not necessary. | Precision lower and vertical loading not difficult. The pitch and roll interaction in pitch control was evident, but did not require too much effort to control. | Only objectionable feature to roll and pitch interaction in pitch control, however, that a roll a significant increase. |
| | | | | | | Selected as a compromise between avoiding excitation of attitude disturbances through coupling and being able to control adequately. | To real difficulty. Longitudinal effect was there as a bit frequency performance in control inputs, but generally, it did not affect ability to control. | Could perform these precisely. Some got into any trouble and could perform them about as good as desired. Coupling evident but it didn't seem to take that much effort to control. | No problem. Did not see the stick still control to small extent. | Precision lower and vertical loading not difficult. Attitude interaction through the coupling. The coupling was evident, but did not require too much effort to control. | Coupling was evident and required some effort to control. Made somewhat smoother control inputs to keep down the effects of coupling, but could still perform task relatively well. |
| 122 | RC1 $\frac{1}{2} \frac{1}{2}$ $\frac{1}{2} \frac{1}{2}$ | A-7B | 0.30 | 0.30 | 0.30 | Set to get desired control response for maintaining aircraft attitude | During air taxi was hampered by coupling between pitch and roll axes. This degraded ability to maintain ground track and to stay with precision. Also, because of increased attention required, height control and longitudinal control was degraded. | Pitch and roll coupling was really apparent. Control of heading was degraded because of this. | Not a lot for difficult. Only small amount of about rotation was required. | Precision lower performance was fairly good but not as good as required. Coupling was evident, but did not require too much effort to control. | Not objectionable. Precision was the coupling between the pitch and roll axes. Vertical was fairly high and had to use relatively small control inputs. |
| | | | | | | Selected to get the attitude response desired and also to not excite the coupling | Could perform task relatively well, but pitch and roll axes showed some coupling. This was not a problem, but it did require some effort to keep down the effects of coupling, but it did not seem to take that much effort to control. | Longitudinal pitch axis was not too difficult, although tended to put some lower rates to control. It did not seem to take that much effort to control. | Did not perform this as precisely as desired. Was to still be somewhat difficult. Did not seem to take that much effort to control. | Precision lower and vertical loading not too difficult. Difficultly coupling in evident. | The coupling is objectionable and requires some effort to attenuate it and control adequately. |
| 123 | RC1 $\frac{1}{2} \frac{1}{2}$ $\frac{1}{2} \frac{1}{2}$ | A-7B | 0.30 | 0.30 | 0.30 | Selected to get desired attitude response | Notion were small oscillations in both pitch and roll due to apparent control coupling, but did not seem to be a problem. Could still perform task precisely without excessive attitude changes. | Could be performed precisely. Coupling did not detract from ability to perform task. | Not difficult. Could keep attitude rate in control quite well. | Precision lower and vertical loading not too difficult. Coupling between pitch and roll was not a problem, but at a low level, not difficult to control. | Only slightly objectionable feature is the coupling. |
| 124 | RC1 $\frac{1}{2} \frac{1}{2}$ $\frac{1}{2} \frac{1}{2}$ | A-7B | 0.30 | 0.30 | 0.30 | Set to achieve desired response for maneuvering | Air taxi performance was good. Could hold ground track and maintain desired point quite easily. Control deflections rather small and low frequency. Control about all axes was good. | Presented no particular problems. | Very little time required for taxi entry a good. | Precision lower performance was very good with minimal stick effort required. The dynamic and control inputs of the aircraft did not affect attitude rate. | Overall the configuration was very good and had good control response and low stick sensitivities. |
| | | | | | | Selected to get desired attitude rate | Attitude control seems fairly low frequency and relaxed, no oscillations. Some coupling evident, but low order and does not present any real problem. Can maneuver and stop precisely. | Can perform the task stop precisely. Some small pitch and roll oscillations but they are low frequency, low amplitude. | Performed this quite precisely. Used a big stick control to some extent. | Precision lower and vertical loading not too difficult. Secondary qualities in question, but no interaction between heading and roll, low level, not difficult. | Some minor objection to the coupling but this is not a big problem. |
| | | | | | | Selected to get the attitude response desired and also to not excite the coupling | Could perform this precisely in both pitch and roll directions. No problem. No large attitude changes developed. | Can stop quickly and precisely both in pitch and roll. The slight coupling but it really does not affect control much. | Not difficult. Can stop quickly and precisely, relatively easy to control. No coupling evident, but not a big problem. | Precision lower and vertical loading not too difficult. Coupling between heading and roll was evident, but not a big problem. | No real objectionable feature. Coupling is objectionable, but does not present any great difficulties. Slightly more configuration, easy to control. |
| 125 | RC1 $\frac{1}{2} \frac{1}{2}$ $\frac{1}{2} \frac{1}{2}$ | A-7B | 0.30 | 0.30 | 0.30 | Set for maneuvering response of the aircraft | No good control characteristics during air taxi. Could hold ground track quite well and stop at desired point. Control deflections were relatively low magnitude and low frequency. | Assumed a little bit by coupling between pitch and roll. During taxi, could control inputs and high angular rates. | Performance was good, little control effort required. Control activity was about as required. | Precision lower performance was good and attitude control activity required. | Not objectionable. Precision was the coupling between the pitch and roll axes. Vertical was fairly high and had to use relatively small control inputs. |

TABLE B-V (Concluded)

| Case | Conf. Parameters | Pilot's Rating | Pilot's Rating | Pilot's Rating | Pilot Comments | | | | | |
|------|--|----------------|----------------|----------------|--|---|---|--|---|---|
| | | | | | Selection of Control Sensitivity | Maneuverability | Quick Steps | Thrust-Over-Byt | Precision Hover, Vertical Landing, Secondary Displays | Overall Evaluation |
| 125 | BC1 $\lambda_1 = 2$ $\lambda_2 = -2$ $\lambda_3/\lambda_4 = -0.25$ $\lambda_5/\lambda_6 = -0.25$ | B-75 | 0.216 | 4.5 | Selected to get desired attitude response | Attitude response fairly relaxed, but appreciable amount of coupling present. Especially noticed pitch inputs when rolling and vice versa. Disturbing and required some attention. Could perform the task adequately, but attitude control required some attention. | Performed fairly well, although not too precisely. Coupling introduced attitude motions that were annoying. | Didn't do this very well for some reason. Not too difficult but should have been able to perform more precisely. | Precision hover and landing as problem. Pitch characteristics affected control of roll and vice versa. | Coupling was significant enough to disturb aircraft and require more attention to attitude control than would like. |
| | | B-80 | 0.110 | 4 | Selected to get the response desired and to help control the effects of coupling | Occasionally not too difficult. Could maneuver longitudinally and laterally with precision, but very definitely some coupling effects that needed corrective inputs. | Coupling quite evident, especially when making rapid attitude changes. | Not difficult. Could perform it rapidly and precisely. Used the wing tilt control to a limited extent. | Precision hover and vertical landing not difficult. Coupling definitely affected control, although it didn't appear to cause a deterioration in performance. | Its coupling between roll and pitch was objectionable, looked like rate coupling. This was annoying, but it didn't lead to a loss of precision. |
| 126 | BC2 $\lambda_1 = 4$ $\lambda_2 = -4$ $\lambda_3/\lambda_4 = 0.5$ $\lambda_5/\lambda_6 = -0.5$ | B-75 | 0.112 | 7.5 | Selected as a compromise between that needed to control attitude motions and that which didn't cause pitch and roll response | Difficult to perform. Lot of somewhat unpredictable attitude motions both in pitch and roll. Apparently a lot of it is due to pitch and roll rates. Got into some fairly large attitudes. Can't perform this with much precision. | Also difficult to perform. Annoyed by coupling. Can't perform this task precisely. | Got into some large attitude motions, a lot of which seem almost unpredictable. Tended to change attitude very abruptly. Difficult to stabilize attitude. | Precision hover and vertical landing not too difficult, but quite precise. Seems to be a lot of interaction between pitch and roll which is quite disturbing. | Objectionable features are the large amount of coupling and the rapid, fairly unpredictable response that it brings about in pitch and roll. |
| 127 | BC2 $\lambda_1 = 2$ $\lambda_2 = -2$ $\lambda_3/\lambda_4 = -0.25$ $\lambda_5/\lambda_6 = -0.25$ | B-75 | 0.142 | 6.5 | Selected to help get control of attitude oscillations | Difficult to perform precisely. Pitch and roll is constant oscillation. Significant amount of compensation required to maintain ground visibility and to stop accurately. Some relatively unpredictable motion in pitch and roll due to coupling. | Difficult to perform precisely, must be very careful about control inputs. Have to watch attitudes closely when executing pitch steps. Get into fairly large attitude oscillations. | Remained over the spot fairly well, but went into large pitch and roll oscillations while doing so. Wing tilt control used to limited extent. | Can perform hover, but not the attitude excursions are significant. Fair amount of interaction or coupling due to the light sampling. | Objectionable features: coupling response to turbulence and lack of damping. Difficult case to control. |
| 128 | BC2 $\lambda_1 = 2$ $\lambda_2 = -2$ $\lambda_3/\lambda_4 = -0.25$ $\lambda_5/\lambda_6 = -0.25$ | B-75 | 0.142 | 6.5 | Selected to get control of the pitch and roll oscillations | Fairly difficult task. Lot of attention must be paid to attitude control. Difficult to stabilize selection and stop precisely, but can be done adequately. | Can perform task, stop precisely, but tend to introduce a lot of pitch motion and roll motion. Have to worry about suppressing those oscillations. | Difficult to perform because one's look away from attitude and check the heading indicator without introducing fairly significant attitude errors. Use the wing tilt to moderate effect. | Precision hover and landing not too difficult, but both required attention. | Objectionable features: response to turbulence, coupling, lack of damping. Difficult case. |

PILOT COMMENTS: THE STUDY OF LONGITUDINAL
INDEX THRUST-VECTOR CONTROL
Flying Qualities Results Given in Table A-VII

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TABLE B-VI (Continued)

| Flight Elements | | | | | | | | | | |
|-----------------|--------------------|-----------------------|--------------------|-------------------|--------------------------------------|---|--|--|--|---|
| Case | Ref. Parameters | Pitch, θ , deg | Roll, ϕ , deg | Yaw, ψ , deg | Direction of Control Data, Utilities | Maneuvering | Quick Steps | Turn-Over-a-Step | Transition Array, Vertical Landing, Sensory, Dynamics | Overall Evaluation |
| 10 | 50 7-20 deg/sec | 4-75 | 0.375 | 5 | NOT ELASTIC | Quite good sensitive in all cases. Air taxi maneuver somewhat difficult and requires constant attention. Being able to independently control longitudinal position with thrust vector somewhat helpful. However, lift rate was too high to do to land position control with an attitude change, then follow up with thrust tilt change. | Maneuvering longitudinally required considerable anticipation and could not stop very accurately at desired point. | Vertical quite high due to gust and some wind effects on high aircraft mass. Thrust vector control helped somewhat but still difficult task. | Precision lower performance fairly good; however, required moderate vertical. Used thrust vector control to control longitudinal position during hover. | Not objectionable features. The high gust sensitivity in pitch, roll and position control of aircraft. Independent thrust vector control may have helped somewhat but still required considerable pilot workload. |
| | | 4-75 | 0.375 | 5.5 | | Could perform longitudinal maneuvers quite accurately, stop precisely and hold position fairly well. Some roll attitude changes. Almost all control input came using just thrust vector and a little high thrust rotation rate. | Could perform quite well. Could maneuver rapidly and stop quite precisely and hold position relatively well. Some difficulty judging just exactly when to initiate thrust rotation. | Could perform this better than controlling position with attitude changes. Could correct position errors quite rapidly. | Could stay within square root of size. Slipped out slightly every now and then, but generally could hover precisely. No problem landing. | High like a little more attitude stability. Attitude every now and then drifted off and then drifted off and introduced some error. Out efforts on attitude were significant. High rate of thrust angle rotation was a little more to control position. |
| | | 4-75 | 0.375 | 5 | | Could maneuver longitudinally relatively well and stop precisely, not bothered by large drag, particularly laterally. Due to effects of gusts active in attitude. | Not such difficulty. Could stop precisely and hold position relatively well. However, had to make very large thrust angle changes and tended to induce fair amount of attitude motion. | Could hold longitudinal position quite well. On perform task better with TVC than without it. | On hover relatively well and land OK. Disturbed somewhat by roll attitude response. | Disturbed attitude response to turbulence and high drag. In general, TVC helped and performance task relatively well. Thrust rotation rate adequate. |
| 11 | 52 7-5 deg/sec | 4-75 | 0.375 | 5 | NOT ELASTIC | Could perform air taxi quite precisely. Although at times desired high thrust rotation rate. Could hold velocities relatively well and stop and hold hover position. | Maneuvering difficult because of load time involved in making inputs to correct attitude. Difficult to predict when to initiate corrective inputs. | Generally not too difficult. With TVC was with attitude. With TVC didn't disturb attitude so much as attitude was highly damped. Response to gusts, but higher thrust rotation rate. | Not too difficult, could perform somewhat with this thrust rotation rate. Vertical landing OK. Some interaction between pitch and roll dynamics. | Disturbed slightly damped attitude response and low rate of thrust rotation. |
| 11C | 52 7-10 deg/sec | 4-75 | 0.375 | 5.5 | NOT ELASTIC | Attitude very lightly damped, quite sensitive to gusts. Fairly high workload for air taxi to control gust disturbances. Some interaction between pitch and attitude control because of attitude on attitude. | Could stop and start quickly, maintain higher velocities and stop abruptly without too much difficulty. | Not too difficult. Maintained attitude position, but in general could hold hover position relatively well. TVC certainly helps. | Precision lower performance fairly well but requires constant effort to offset gust disturbances on attitude. | Not objectionable features. The high gust sensitivity and slightly damped pitch and roll dynamics. TVC does aid longitudinal accuracy. |
| | | 4-75 | 0.375 | 5.5 | | Longitudinal air taxi fairly easy. Could maneuver fairly well. Hold velocities and stop and hover at desired point. Pitch required some attention because it was lightly damped. TVC agreement. Without it would have caused attitude motion because of lightly damped dynamics. | Could stop and start quickly, maintain higher velocities and stop abruptly without too much difficulty. | Not difficult. Maintained attitude position, but in general could hold hover position relatively well. TVC certainly helps. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. | Objected to lightly damped attitude dynamics. TVC helped this configuration. |
| 11E | 52 7-20 deg/sec | 4-75 | 0.375 | 5 | NOT ELASTIC | Could maneuver precisely. Stop without too much difficulty and hold hover position. Adequate thrust rotation rate. Attitude not so well damped, would have expected attitude more without TVC since only small attitude corrections needed. | Could stop and start quickly, maintain higher velocities and stop abruptly without too much difficulty. | Not too difficult. Could hold hover position quite accurately while controlling attitude disturbances. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. |
| | | 4-75 | 0.375 | 5.5 | | Longitudinal maneuver performed relatively well. Just "okay" to disturb attitude and then "okay" after position. With a fair amount of coupling between roll and attitude changes. More load occasionally high. | Could stop and start quickly, maintain higher velocities and stop abruptly without too much difficulty. | Not too difficult. Could hold hover position quite accurately while controlling attitude disturbances. Pitched some significant inputs to pitching moment due to thrust rotation. | Precision lower and landing not too difficult. Actual control affected ability to control longitudinally. | Objected primarily to lack of attitude damping. Thrust vector rate was high, but needed it. TVC definite merit. |
| 11G | 52 7-20 deg/sec | 4-75 | 0.375 | 5 | NOT ELASTIC | Air taxi not too difficult. Could maneuver with desired velocities and stop precisely. Didn't have to put difficulty monitoring thrust angle and display in control of position. | Could stop and start quickly, maintain higher velocities and stop abruptly without too much difficulty. | Not too difficult. Could hold hover position quite accurately while controlling attitude disturbances. Pitched some significant inputs to pitching moment due to thrust rotation. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. |
| 11H | 52 7-20 deg/sec | 4-75 | 0.375 | 5 | NOT ELASTIC | In all, taxi could control position and velocity quite precisely. Stop accurately and hold position with no difficulty. Didn't make any pitch attitude control inputs. Acceptable command was. | Could stop and start quickly, maintain higher velocities and stop abruptly without too much difficulty. | Not too difficult. Could hold hover position quite accurately while controlling attitude disturbances. Pitched some significant inputs to pitching moment due to thrust rotation. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. | Not too difficult. Could hold hover position within square at all times. Attitude oscillations did require some attention. Landing or problem. A little interaction between pitch and roll, not bothering major. |

TABLE B-VI (Concluded)

| Case | Coeff. Parameters | Pitch Sls. Mode | $\frac{Y_{20}}{Y_0}$ | R | Pilot Comments | | | | | |
|------|---|-----------------|----------------------------|-----|------------------------------------|---|---|---|---|--|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stop | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Boundary Dynamics | Overall Evaluation |
| 1112 | RL $Y_0 = 5.0$ deg/sec $Y_{20} = 1.0$ rad/sec ² | R-FB | R.A. ¹ 0.262 | 3 | NOT SELECTED | Easy to perform precisely and hold altitude accurately, stop low-velocity and hold lower position with no problem. | Not difficult, can develop large velocities and stop very abruptly with precision. Develop some small attitude oscillations, but just ignored them. | Not difficult to control to a position, but when turning positive to zero pilot have to correct for slight under; this disturbs slightly from precise control. | Hover control easy, can lower and land precisely. | Attitude control during hover can be somewhat difficult, although there is a landing pattern. Very easy to control position, like thrust vector sensitivity. |
| 1113 | RL $Y_0 = 10.0$ deg/sec $Y_{20} = 1.0$ rad/sec ² | R-FB | R.A. ¹ 0.262 | 3.5 | NOT SELECTED | Not difficult to maneuver and stop precisely. Can hold desired altitude without difficulty. Thrust till control sensitivity has gotten somewhat high, notice attitude motion following thrust rotation. | Can stop precisely. Can build up large velocities and arrest them very abruptly and precisely. High control sensitivity induces some attitude motion. | Not somewhat difficult. Precision control no problem, but once max. have some difficulty in controlling area near stroke on attitude. Not share situation between attitude and longitudinal position. | Precision hover and landing no problem. | Thrust rotation control sensitive somewhat high, induces some attitude errors and tends to induce errors in position. Generally can control longitudinal position quite precisely. |
| 1114 | RC $Y_0 = 5.0$ deg/sec $Y_{20} = 1.0$ rad/sec ² | R-FB | R.A. ¹ 0.255 | 10 | NOT SELECTED | Can't really control it. Attitude changes are too high frequency to follow with thrust action, even trying to reduce large attitude errors position errors get large. Can't control attitude. | Can't perform quick stops. | | Can't hover and tend to lose control quite often. Tend to get confused with lower and can't compensate quite well enough. Thruster doesn't seem to help. | Incoordination between direction that thrust vector pushed to change attitude and direction that control stick pushed to correct for position errors. Can't control sufficiently well to avoid inducing large position disturbances. |
| 1115 | RC $Y_0 = 5.0$ deg/sec $Y_{20} = 1.0$ rad/sec ² | R-FB | R.A. ¹ 0.255 | 10 | NOT SELECTED | Effectively uncontrollable. Can probably stabilize it out but lose control during hover, but when maneuvering the controllability is positive induce much large attitude changes that can't correct them easily enough. | Difficult to control attitude in any high frequency sense with this control arrangement. | | Large attitude changes induced when attempting to hold hovering position. Can't correct attitude rapidly enough and stabilize it well enough to control with any precision or even to retain control of aircraft. | Eventually get into a large attitude oscillations and lose control, even just at hover. Extremely difficult to control attitude and stabilize it. |

TABLE B-VII

PILOT COMMENTS FROM THE STUDY OF LONGITUDINAL AND LATERAL RATE-COMMAND/ATTITUDE-HOLD CONTROL

Flying Qualities Results Given in Table A-VIII

| Case | Inst. Parameter | Pitch Rate | $\frac{p}{\omega_n}$ | FR | Pilot Comments | | | | | |
|------|-----------------------------------|------------|----------------------|-----|--|--|---|---|--|--|
| | | | | | Selection of Control Sensitivity | Maneuvering | Quick Stops | Turn-Over-A-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Remarks |
| 121 | SC1 $M_0 = -2$ $M_0 = -8$ | 2-FB | 0.812 0.975 | 7.5 | Selected to gain control of attitude oscillations and also get desired response. | Very difficult to perform because of large attitude oscillations. Difficult to stabilize pitch and roll, couldn't perform task precisely. Got into some relatively large attitudes. | No problem. Couldn't stop quickly or precisely and very difficult to control attitude within desired limits. | Couldn't perform precisely because of difficulty in controlling pitch and roll attitude. Did use the wing tilt control to small extent. | Hover was subject of all tasks, but drifted around. Unpleasantly the roll dynamics affected pitch control and vice versa. | Objectionable features - large oscillatory motions in pitch and roll and the large response to control inputs. |
| 122 | SC1 $M_0 = -2$ $M_0 = -10$ | 2-FB | 2.100 2.130 | 6.5 | Selected to get pitch and roll rates under control. | Could perform this maneuver fairly well but a high frequency oscillation in pitch and roll was annoying. Too high frequency to control and it affected precision. Still several seconds of sluggishness in roll response. | No problem with longitudinal quick stop. Except for annoying high frequency oscillations; however, lateral quick stop difficult to perform because of sluggishness in roll. | Could perform task fairly well, although the high frequency attitude oscillations were annoying. Used some wing tilt control. | Hover and landing not particularly difficult. | Objectionable features - high frequency oscillation in pitch and roll. Also, roll sluggishness. |
| | | | 2.400 2.400 | 4.5 | Selected to overcome the lags in pitch and roll response. | Maneuver also not too difficult. Had to avoid building up rates which were too large because it was difficult to eliminate them due to lag in roll response. | Quick stop quite difficult. Couldn't stop precisely and hold position steadily because of overshoot and then oscillate back and forth. | Didn't perform task particularly well - had difficulty holding position. Attitude lags might have been a problem. May have been overcontrolling somewhat. Used wing tilt control a fair amount. | Hover not difficult. Vertical landing also no problem. No interaction. | Objectionable features - lag in attitude response and the fact that indicated changes when attention diverted from display. |
| 123 | SC1 $M_0 = -4$ $M_0 = -8$ | 2-FB | 0.004 0.904 | 2 | Selected sensitivity to maintain PIO tendencies. | Required considerable attention because of difficulty in stabilizing command attitudes. Required considerable hand compensation to stabilize and anticipation of desired stopping point to arrest oscillations. Ability to remain within ground track rather poor because of attention required to control heading, landing and attitude control deteriorated. Control deflections had to be very small and too infrequent to avoid getting into PIO situations. | Difficult because of difficulty commanding large rapid attitude changes. Heads were rate damping. | Required considerable concentration because of difficulty in maintaining pitch and roll control. Very little wing tilt required. | Hover only moderately difficult but some difficulty establishing a precise hover position. | Most objectionable feature was large amount of hand compensation required to control and stabilize attitude. Had considerable tendency toward PIO's, particularly in pitch. |
| | | | 0.904 0.904 | 5 | Selected to get control of attitude oscillations and quickly desired pitch and roll rates. | Could perform task with only moderate precision. Attitude oscillations made it difficult to stabilize on ground track precisely and stop precisely. | Again found it difficult to stop precisely and roll out as precisely as desired because of oscillatory pitch and roll response. | Generally able to do this alright. Wing tilt control used a fair amount. | Not too difficult, but some fair amount of pitch and roll oscillations. Very little interaction. | Objected to oscillatory pitch and roll characteristics. |
| 124 | SC1 $M_0 = -4$ $M_0 = -10$ | 2-FB | 3.304 3.302 | 2 | Selected to get necessary pitch and roll rates. | No problem, could perform precisely. Very agreeable case. | No problem, could perform precisely, no undesirable attitude oscillations. | Not difficult. Did use wing tilt control to a small extent. | Neither hover nor landing was difficult. Both performed precisely, although had a little difficulty in hover, maybe because of high sensitivities. Difficult to stabilize on given position. | Objectionable features - roll rate. |
| 125 | SC1 $M_0 = -4$ $M_0 = -12$ | 2-FB | 1.192 1.526 | 4 | Selected to get attitude rates desired and also to help control slight oscillatory tendency in pitch and roll. | No problem longitudinally. Laterally generally no problem except some tendency to oscillate when rolling out, although these oscillations are relatively easy to control. | No problem in longitudinal; however, when making lateral quick stop have tendency to develop some undesirable oscillations when trying to roll out rapidly. | No problem. Did use wing tilt control to some small extent during turn. | Precision hover and vertical landing performed precisely. No interaction. | Objectionable features - tendency to oscillate when making abrupt roll changes. |
| 126 | SC1 $M_0 = -6$ $M_0 = -10$ | 2-FB | 2.208 2.200 | 2.5 | Selected to get attitude response earlier. | Could perform maneuver quite well. Attitude very stable, no attitude oscillations noticeable. Didn't get into large attitudes. In general could perform fairly well. | Same story, although attitude quite stable. Slight lag. Seemed to have trouble with lags in response to control commands. Used wing tilt control to slight extent. | Not difficult because attitude quite stable. Seemed to have some trouble with lags in response to control commands. Used wing tilt control to slight extent. | Hover and vertical landing no difficulty. No interaction between axes. | Objectionable features - some slight sluggishness in pitch and roll, especially roll. However, attitude very stable. Highly damped. |
| | | | 4.182 4.696 | 3.5 | Could perform relatively well. Slightly annoyed by sluggishness in control response. Also had to concentrate to avoid developing attitudes errors. | Could perform maneuver quite well. Attitude very stable, no attitude oscillations noticeable. Didn't get into large attitudes. In general could perform fairly well. | Could perform maneuver quite well. Attitude very stable, no attitude oscillations noticeable. Didn't get into large attitudes. In general could perform fairly well. | Not too difficult. Made significant use of wing tilt control. | Could hover fairly well. Landing not difficult. No real interaction between pitch and roll. | Lags in pitch and roll response affected control. Also attitude errors integrate rapidly when attention is diverted. |
| 127 | SC1 $M_0 = -8$ $M_0 = -10$ | 2-FB | 1.004 2.240 | 4 | Set control sensitivity to achieve desired response to control inputs. | Fairly easy to perform although anticipation was required to stop at desired hover point due to low translational drag. Could hold heading and attitude quite well during air taxi maneuver. | Performance fairly good although could not achieve rapid attitude changes without large control inputs. | Had a little difficulty trying to maintain hover position because of concentration required to hold attitude. Very little wing tilt control required. | Hover and landing performance very good and required very little workload or control motion. | Most objectionable feature was if a control input were held, it resulted in attitude changes if attention directed elsewhere. May need more training with this control system. |
| 128 | SC1 $M_0 = -10$ $M_0 = -15$ | 2-FB | 3.260 3.344 | 3 | Responded almost as rate command system as rate sensitivity to achieve desired rate response. | Relatively easy and performance was quite good. Could hold heading and attitude quite well during maneuver and control deflections relatively small at low frequency. | Slightly annoying, couldn't change attitude as rapidly as desired without rather large control inputs. | Wasn't too difficult. Very little wing tilt control required, but did require concentration because of low drag. | Precision hover relatively easy. Performance good and got disturbances hardly noticeable. | Slightly objectionable feature was attitude control during quick stops. |

TABLE B-VII (Concluded)

| No. | Test Parameters | Pilot | No. of Trials | No. of Errors | Performance | | | | | |
|------|--|-------|---------------|---------------|---|---|--|---|---|---|
| | | | | | Retention of Control Characteristics | Interfering | Quick Stops | Disturbances | Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 1205 | RC $\eta_0 = -10$ $\eta_0 = -50$ | 3-75 | 5,530 | 3 | Selected to overcome sluggishness in pitch and roll responses. | Not at all difficult. Didn't get into any large attitude changes and didn't have any previous holding velocity and stopping at desired point. | Quick stop no problem. Could stop precisely. Quick stop somewhat more difficult. Had a little difficulty stopping but didn't tend to oscillate too much. | Could perform relatively well. Not too difficult. Used wing-tilt control to some extent. | Never and vertical landing not difficult. | Still a little sluggishness in attitude response. Everything well handled. Interfered by fact that when looking at heading indicator, tended to drift away in attitude. |
| 1207 | RC $\eta_0 = -2$ $\eta_0 = -10$ | 3-75 | 1,750 | 5 | Selected to get control of attitude oscillations and to get desired attitude response. | Not too difficult. Some annoying tendency to oscillate in pitch and roll; however, these are low frequency. | Generally not too difficult. Attitude oscillations, although low frequency, large enough amplitude to affect ability to control. | Difficult. Most account for high drag with wing tilt control. Attitude oscillations make difficult to concentrate on position. | Never and vertical landing not too difficult. | Oscillatory attitude characteristics and high drag which make it difficult to turn down spot precisely are objectionable. |
| 1210 | RC $\eta_0 = -2$ $\eta_0 = -25$ | 3-75 | 2,150 | 5 | Selected to get rule of response desired to overcome effects of attitude stabilization. | Somewhat difficult to perform because of higher frequency oscillations in pitch and roll. No large enough amplitude or low enough frequency to affect position, but were a distraction and made attitude control a problem. | Difficult to stabilize attitude at times following roll-out during lateral quick stop. | Some difficulty due to distractions in attitude. High frequency oscillations. Fine tilt control used a good bit. | Could not hover too precisely due to high frequency attitude oscillations. Vertical landing no problem. Some interaction between pitch and roll dynamics. | Fairly continuous, low frequency oscillations in attitude objectionable. |
| 1211 | RC $\eta_0 = -4$ $\eta_0 = -16$ | 3-75 | 1,620 | 15 | Selected to get desired attitude rate. | Generally could perform maneuvers quite precisely. Wide response in pitch and roll. Possibly slight tendency toward low-level oscillations, but presented no problem and attitude characteristics. | No real difficulty performing. Could stop accurately. Attitude quite controllable, predictable. | Performed reasonably well. Could concentrate on position without developing large attitude errors. Wing tilt control used a great deal. | Never and vertical landing no problem. No interaction between pitch and roll. | Objectionable features were high drag in pitch and roll and perhaps some lack of turning. |
| | | | 2,175 | 5 | | Could perform relatively well but experienced some problems because of slightly higher, high frequency oscillations in pitch and roll. Had to be careful not to excite them. | Could perform with adequate precision, but there was a lot of roll action during quick stop. Attitude is almost constant oscillation during fast. | Could perform with adequate precision. However, pitch and roll were in almost constant oscillation. Had to be quite careful not to excite fairly large attitudes when starting attitude. No landing. Used wing tilt control good bit. | Never and landing not difficult. Possibly some interaction between pitch and roll. | Slightly tapered, high frequency oscillations in pitch and roll were disagreeable. Oscillatory attitude ability to control a good deal. |
| 1212 | RC $\eta_0 = -4$ $\eta_0 = -25$ | 3-75 | 2,550 | 3 | Selected to get the attitude response needed to overcome attitude stabilization. | Not difficult except for effects of rather large drag. Used attitude response characteristics, well shaped. No oscillations and didn't get into unexpected attitudes. | Generally could perform fairly well, although high drag held him somewhat usually. | Handled this alright. Have to take it slow because of high drag and have to be careful with wing tilt. Attitude presented no distraction. | Never and vertical landing not difficult. | High drag objectionable, but attitude characteristics very good. |
| 1213 | RC $\eta_0 = -4$ $\eta_0 = -25$ | 3-75 | 1,630 | 3 | Selected to get desired rate of change in pitch and roll. | Not particularly difficult to maneuver. Attitude quite predictable, well shaped. Very slight tendency toward some low frequency oscillations but no problem controlling. | Generally no problem, although possibly could have used a little more sensitivity to roll. Some difficulty a compromise between fast needed to roll out to lateral quick stop vs requirements for lower. | For difficult. Too slow and used wing tilt control extensively. | Never and landing not difficult. No real interaction. | Only objectionable feature might be high drag and slight tendency toward low frequency oscillations in pitch and roll. |
| 1214 | RC $\eta_0 = -4$ $\eta_0 = -25$ | 3-75 | 2,200 | 3 | Selected to get desired attitude rate. | Not difficult performing attitude control. Good attitude characteristics, but high drag tends to make it somewhat difficult to maneuver precisely. | Attitude control good. Generally can perform quick stop precisely. | Good attitude characteristics. No real problem because of large drag. Have to take it slow and use wing tilt control good bit. | Never and vertical landing no problem. No interaction between pitch and roll. | Objectionable feature effects of turbulence on high drag characteristics. Oscillatory attitude characteristics are |
| | | | 3,050 | 5 | | Generally not too difficult, did have oscillatory tendency in pitch and roll response. Could not oscillate fairly well. | In general, could perform quick stop alright but tended to get into pitch and roll oscillations. | Not too difficult. Had to be careful to develop control attitude in pitch and roll because of oscillatory attitude response. Immediately became disturbed attitude when attitude disturbed. | Never and landing not difficult. No real interaction. | Oscillatory pitch and roll response objectionable. Tended to be slow somewhat due to the way it was easily. |
| 1215 | RC $\eta_0 = -10$ $\eta_0 = -50$ | 3-75 | 1,750 | 3 | Not to achieve desired response in pitch and roll for maneuvering fast. | Fairly good performance. Could stop quite well without ground inputs and in-flight control inputs to overcome desired pitch and roll. Control inputs relatively small and low frequency. | Not too difficult but required rather large attitude changes to get desired type action. | General controllable attitude to offset gust and some other effects on drag. This required considerable wing tilt control to turn. | Never relatively easy, but some disturbances required continuous control. Performance quite good. | Performance relatively good. Only slightly objectionable features were some wind and its effects on position response of aircraft. |
| | | | 2,010 | 5 | | Not too difficult. Not too precisely without excessive attitude changes and a little trouble in stopping at desired point. Attitude oscillations in position. | Quick stop no problem. Had a little trouble with a quick stop in stopping at desired point. Attitude oscillations in position. | Some difficulty, although didn't interfere particularly large position errors. Not too much wing-tilt control with direction. | Never and landing not difficult. No interaction. | Objectionable sluggishness in pitch and roll even with large sensitivity. Everything quite well done. |

TABLE B-VIII

PILOT COMMENTS FROM THE HEIGHT CONTROL STUDY OF THE INTERACTION BETWEEN HEIGHT VELOCITY DAMPING AND THRUST-TO-WEIGHT RATIO

Flying Qualities Results Given in Table A-IX

| Case | D.A.C. Parameters | Pitch Mode | T ₀ | P | Pilot Comments | | | | |
|------|----------------------------------|------------|----------------|---|---|--|---|---|---|
| | | | | | Selection of Control Sensitivity | Manoeuvring | Sink Stops | Precision hover, landing sequence and recovery dynamics | Overall Evaluation |
| N1 | N1 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 3.46 | 9 | Set height control sensitivity in an attempt to stabilize altitude. | Very difficult because of difficulty in controlling altitude. Altitude was very, very lightly damped and required extreme concentration to gain even minimal altitude stability. As a result, the remainder of the test suffered considerably. | Also difficult to perform because the large altitude changes produced altitude errors which were difficult to control and often resulted in PIO-type situations in altitude. | Hover difficult because of altitude control. Had difficulty holding altitude within 75 ft of the desired level. Altitude control activity high. | Most objectionable feature was the lack of damping in altitude. Intense pilot concentration was required to retain control. |
| | | B-78 | 3.14 | 7 | Selected in an attempt to get height under control. | Quite difficult, can't perform the task as precisely as desired because have to pay so much attention to height control. Altitude varies 20 ft upward to 140 ft. Difficult to keep under control. | Can't be performed properly because must pay so much attention to height. | Could perform fairly well. Didn't do much height too much while hovering. Configuration was good enough such that could hold hover position fairly well. The landing sequence performed reasonably well, at least in height; however, neglected hovering position somewhat. Could land it safely. | Initially needs more height damping. |
| | | L-78 | 3.01 | 7 | Selected in an attempt to gain control of altitude oscillations. | Could maneuver longitudinally without too much difficulty, however, height oscillated 750 ft. Lateral maneuvering was difficult. | Performing lateral quick stops was quite difficult. Tended to have altitude go up to 100 ft or more. | Could hold altitude within 750 ft in hover. Refinable interaction between height and particularly lateral control. Could change altitude, but tended to oscillate a fair amount about it. | Needs more height damping. |
| N2 | N2 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 2.98 | 4 | Set height control sensitivity to get desired altitude response for air taxi and landing sequence. | Altitude control fairly good, could devote attention to control of other axes during the air taxi and quick stop maneuvers. Relatively easy and very little wing tilt was required during turn. | Could hold height if considerable amount of attention paid to it. Probably quick stop maneuvers suffered somewhat and height tended to slip away. | Precision hover required very little control activity and altitude could be held fairly well. The landing sequence maneuver required a little attention to stop at desired altitude, but otherwise was not too difficult. | A little more altitude damping needed to make it a satisfactory configuration. |
| | | B-78 | 3.12 | 4 | Selected to get desired altitude response. | Could perform task while holding height fairly well, although height required attention. Held height within say 75 ft. | Could hold height if considerable amount of attention paid to it. Probably quick stop maneuvers suffered somewhat and height tended to slip away. | Could hover quite accurately. Didn't have any problems holding height. Hover position wasn't affected too much by turbulence, consequently, there was little to disturb height; no large altitude changes necessary to correct hover position. In landing sequence, going from 80 ft down to 20 ft, had difficulty arresting the descent rate and holding it. Had a tendency to overshoot desired altitude. Could land without too much difficulty, but had to do it carefully. | Think L ₀ level is a little too low, would like to be able to take attention off height a little more. Can't hold altitude much better than 75 ft at best. |
| | | B-78 | 2.57 | 4 | Selected to get desired rate of response in height. | Generally could perform this task fairly well, at least longitudinally. When maneuvering laterally, developed some height oscillations which were somewhat difficult to damp out. Paying attention to these and trying to get height under control did detract from ability to perform the lateral maneuver. | Generally could perform these relatively well. Had some trouble with the lateral quick stop and the coupling into height. Would like to see a little more height damping. | No problem hovering and holding hover altitude. Could come down and stop fairly well at 20 ft and then come back up to 80 ft. Had to land fairly accurately, but this wasn't a very great problem. Some interaction between height and control of roll. | Didn't like tendency to build up height oscillations when attempting to maneuver laterally. Had to pay attention to height but the damping was just slightly inadequate. |
| N3 | N3 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 3.04 | 3 | Selected height control sensitivity to obtain desired altitude response for takeoff and landing. | Air taxi was relatively easy as altitude required only moderate amount of attention to hold during the maneuver. Air taxi required relatively small pitch and roll changes, however, i.e. to low drag, stopping position had to be anticipated. | Had no particular problems and altitude control was no problem as long as height control was coordinated with large altitude changes. | Control motions and pilot effort during precision hover were very low. Had very little trouble arresting sink rate during the landing sequence and the subsequent climb back to 80 ft. | A little more height damping might be desirable but this level is quite adequate. |
| N4 | N4 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 3.20 | 2 | Selected to get desired response to collective inputs for changing altitude. | Air taxi was relatively easy because very little attention was required to control altitude. | Quick stop maneuver quite easy. | Precision hover required virtually no inputs on the altitude control to maintain the altitude within 75 ft of the nominal hovering altitude. | Very good height control, has adequate damping. |
| N5 | N5 $T_0 = 0.0$ $T/W = 1.0$ | B-78 | 3.05 | 7 | Selected in an attempt to control altitude oscillations. | Developed coupling between height and both longitudinal and lateral axes when attempting to maneuver. Seemed to have difficulty holding height during the longitudinal maneuver. | During the longitudinal quick stop just about touched down because of the low thrust and lack of hovering. Height was consistently going into relatively large oscillations, 20 ft or so. | This wasn't too bad. Could stabilize height fairly well and keep hovering position under control quite well. During landing sequence almost touched down during descent to 20 ft. Had to be very careful because of the low control power. Was able to stabilize fairly well after desired altitude achieved. Needs more thrust and more damping. Definite interaction between the height dynamics and roll and pitch dynamics. | Objectionable feature is the distinct lack of height damping and low thrust. |
| N6 | N6 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 3.0 | 7 | Had adequate thrust for takeoff but had difficulty stopping at desired maneuvering altitude of 40 ft. Had some problems controlling altitude during the air taxi and turn-over-and-stop maneuvers. | | Control of altitude required considerable pilot attention in quick stops. | Hovering performance fairly good, but required some attention to control altitude. Had a great deal of difficulty in arresting sink rate during the descent to 20 ft. Thrust was clearly quite inadequate and the configuration lacked height damping. | Aircraft needs both increased thrust and increased height damping. |
| N7 | N7 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 3.0 | 6 | Climb-out following takeoff was very slow due to lack of thrust. Had some difficulty stopping and maintaining desired maneuvering altitude at 40 ft. Air taxi required considerable pilot concentration on altitude control. Somewhat difficult to stay within 25 ft of the desired altitude. | | Particularly difficult due to the upsets in altitude. During the lateral quick stop briefly touched down. | Precision hover not too difficult after the desired altitude was stabilized, but stabilizing this altitude was somewhat of a problem and required considerable effort. Arresting sink rate during the landing sequence maneuver required that only small sink rates could be developed. | There were two equally objectionable features: (1) the lack of thrust for arresting sink rate and climbing out and (2) the insufficient altitude damping. Considerable effort required to avoid developing high sink rates. |
| N8 | N8 $T_0 = 0.0$ $T/W = 1.0$ | A-78 | 3.0 | 6 | Configuration very sluggish during lift-off. Could not establish very high rate of climb; however, had no difficulty at all establishing desired altitude. During the air taxi had no problem controlling altitude. | | Altitude was upset a little more and did notice a limitation on thrust in arresting sink rate. | Hovering performance was very good and was not bothered by lack of either thrust or altitude damping. During landing sequence had to be careful not to develop too high a sink rate, but didn't have too much difficulty arresting sink rate as long as care was used. Climb out again to 80 ft was very slow and sluggish. | Most objectionable features were (1) lack of thrust which was particularly annoying during climb out and (2) annoyance in arresting sink rate, although this problem was not too severe. |

TABLE B-VIII (Continued)

| Case | Conf. Parameters | Pilot-Size, Mode | T ₀ | FR | Pilot Comments | | | | |
|------|--|------------------|----------------|-----|---|--|--|---|---|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Precision Hover, Landing Sequence and Secondary Dynamics | Overall Evaluation |
| K29 | BC1 $z_{\eta_0} = z_{\eta_0}^*$ -0.35 $7/N=1.02$ | A-7B | 3.0 | 4 | | Had to pay fairly close attention to height control when maneuvering. Had to lead inputs fairly much in order to arrest descents and had to be careful about building up descent rates that were not too large. Couldn't take attention off height control. Although I could perform the maneuvers fairly well, it affected their precision somewhat. Also, don't think height hold any better than about ± 10 ft on the average, maybe somewhat less. | Required considerable attention to control altitude. | Hover was not too difficult to perform and could stabilize attitude fairly well. Had difficulty going down to 20 ft and stabilizing there, tended to oscillate up and down. Also, had to be very careful with collective inputs. Significant amount of time before reaching desired 20 ft position. Could land safely, however. | Would prefer to see a little more T_0 and also more thrust. |
| K210 | BC1 $z_{\eta_0} = z_{\eta_0}^*$ -0.25 $7/N=1.02$ | A-7B | 3.0 | 4 | | Adequate thrust for takeoff. Had no problem stopping at desired hovering altitude. All constant altitude maneuvers were relatively easy to perform. Did not have to concentrate much on altitude and held altitude relatively constant. | No problems. | Precision hover performance was very good and there was very little control activity required. Thrust was slightly deficient when attempting to arrest sink rate so had to anticipate the desired altitude while descending by applying thrust with anticipation. | Only slightly objectionable feature was the limitation on thrust values was noticed only when arresting sink rates. |
| K211 | BC1 $z_{\eta_0} = z_{\eta_0}^*$ -0.4 $7/N=1.02$ | A-7B | 3.0 | 5 | | Climb out following takeoff was very slow as there was inadequate thrust to develop any significant rate of climb. However, damping seemed quite good so had no trouble stopping at desired hovering altitude. Altitude control was quite easy during all of the constant altitude maneuvers, including air taxi and turn-over-a-spot. | No problem controlling altitude. | Hover performance good. Little effort required. Didn't seem to have much trouble arresting sink rate during the landing sequence. However, had difficulty climbing back up to 40 ft, there was just inadequate thrust available. Landing was not particularly difficult as long as sink rate wasn't allowed to get too high. | Biggest objections were (1) lack of thrust for developing suitable climb rates for taking off and climbing to desired altitudes and (2) inadequate thrust for arresting high rates of sink. |
| | | A-7B | 3.0 | 4 | | No difficulty, quite easy to hover and maneuver and to stop precisely both vertically and laterally. Could hold height quite accurately while doing this little attention required. | Can perform without difficulty and can go to relatively large altitudes without having altitude affected significantly. | No difficulty, can hover precisely and hold altitude without difficulty. In landing maneuver can come down to 20 ft without too much difficulty. Must perform this task relatively slowly because can't arrest large sink rates; however, the large T_0 aids in performing task. Very difficult to climb back up to 40 ft altitude because of low thrust. Can land quite easily, but again have got to do it relatively slowly. | Only objectionable feature is that it is very difficult to climb to any altitude. Response is much too slow and have some difficulty arresting sink rates, but this is not a significant problem. |
| | | A-7B | 2.95 | 5 | Selected to get desired response to control inputs is height. | Could maneuver quite well. Some coupling between height and roll inputs, but generally height very stable, very well damped. Only complaint with height control is lack of thrust. It takes a long time to climb out. However, can descend and arrest descent very smoothly and precisely. | No problem, but during the lateral quick stop did couple in some height motion. | No problem. Landing sequence not difficult to perform, but annoyed by inability to climb out as quickly as desired. Much too sluggish in climbing. | Only objectionable feature is lack of thrust which restricts rate of climb, but well damped and can arrest descents precisely. |
| K212 | BC1 $z_{\eta_0} = z_{\eta_0}^*$ -0.005 $7/N=1.05$ | A-7B | 3.07 | 6.5 | Selected primarily in attempt to control height oscillations. | Could perform the longitudinal maneuver fairly accurately and hold hover within ± 10 ft. Lost precision in lateral maneuver because of concentration required on holding height. Definite interaction between height control and ability to control laterally. | Again longitudinal was not too bad. Laterally didn't build up too many large errors but still feel that height control is much too poorly damped to control adequately. | Hover wasn't too difficult. Height remained in constant oscillation, but not to particularly large amplitudes or as large as they were during the maneuvering portions of the tasks. Could descend to about 20 ft and hover there with relatively small altitude oscillations and then go back up to 40 ft. Height dynamics definitely affected ability to control lateral position. | Definitely needs more height damping to reduce attention required on height control. |
| K213 | BC1 $z_{\eta_0} = z_{\eta_0}^*$ -0.05 $7/N=1.05$ | A-7B | 3.01 | 6 | Selected to get desired rate of change of height and to help get the height oscillations under control. | Air taxi not difficult. Holding height within ± 10 ft while maneuvering longitudinally, but when maneuvering laterally tended to develop larger height oscillations as much as 20 ft or so. Think height control did affect ability to perform maneuvering task to some extent. Difficult to stabilize height. Height was in almost continuous oscillation. | Longitudinal quick stops could be performed better than lateral ones, however, in both introduced some upsets in height. These were especially pronounced for lateral quick stop when altitude diverged by about 30 ft. Unfortunately, height was in pretty much constant oscillation during performance of quick stops. | Hover not too difficult. Could keep the height oscillations to within ± 5 ft. Had sufficient control power to perform landing sequence, but needed some damping. Had to lead height control to arrest climb and descent rates. Could perform vertical landing safely. Height dynamics did affect ability to control during the lateral quick stop. Tendency to let height diverge and concentrate on the lateral maneuver. | Objectable feature was the lack of height damping. Control power seemed adequate. |
| K214 | BC1 $z_{\eta_0} = z_{\eta_0}^*$ -0.125 $7/N=1.05$ | A-7B | 3.0 | 3 | | Thrust adequate for takeoff and didn't have too much trouble stopping at the desired altitude following climb out. Height control required a little bit of attention while performing the constant altitude maneuvers, but both thrust and damping seemed to be adequate. | No problem with this task. | Precision hover performance was quite good and required very little attention. During the landing sequence maneuvers seemed to have adequate thrust for arresting sink rate and for climbing back to the 40-ft altitude hover. | |
| | | A-7B | 3.0 | 4.5 | | Air taxi could be performed reasonably well, but had to pay significant amount of attention to altitude. Tended to drift away and had to correct and lead control corrections to stabilize on altitude. | Could be performed fairly well. Could go to large altitude changes without abrupt changes in altitude. However, again altitude tended to creep off and needed stabilization. | Could hover fairly well but had to pay fair amount of attention to altitude. Had some difficulty stabilizing on new altitudes when descending and in coming back up to 40 ft. Had to lead control input to stabilize height. Also had to approach the landing somewhat cautiously. | Didn't feel that altitude could be changed easily enough. Had to be somewhat careful with altitude control. Like to see more height damping. |

TABLE B-VIII (Continued)

| Case | Test Parameters | Pilot's Note | \bar{z}_0 | PS | Pilot Comments | | | | |
|------|---|--------------|-------------|-----|--|--|--|---|--|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Precision Hover, Landing Sequence and Secondary Dynamics | Overall Evaluation |
| MC14 | MC1 $Z_{\eta_0} = Z_{\eta_1} = 0.125$ $T/N = 1.05$ | B-PC | 2.62 | 3 | Selected to get desired height response. | No problem performing maneuver longitudinally; laterally might have omitted a little height motion, but apparently height is sufficiently well damped that did not get into any significant height position changes. | Could perform both longitudinal and lateral quite stop fairly well without upsetting height. Height is relatively easy to control, stable. | No problem holding hover position or altitude. No problem performing landing sequence. Could stop abruptly with only a slight amount of compensation. Height position well damped at real interaction between different axes. | No real objectionable features. Sufficient damping, no apparent lack of control power. |
| MC15 | MC1 $Z_{\eta_0} = 0$ $Z_{\eta_1} = 0.25$ $T/N = 1.05$ | A-FB | 3.0 | 6 | | Because of inadequate thrust, takeoff was relatively sluggish, but had no difficulty establishing desired maneuvering altitude. During constant altitude maneuver performance was fairly good. Lack of altitude damping was not a particular problem. Hovering turn required only a small amount of wing tilt trim. | Used altitude somewhat but the only deficiency is a lack of thrust for arresting these altitude disturbances. | Precision hover performance was excellent and required very little effort. Damping was fairly good. During the landing sequence, the only problem was arresting high sink rates quickly, this required control to develop only minimal sink rates. | Absent only objectionable feature seemed to be lack of thrust for arresting sink rates and for developing desired climb rates. Requires attentive attention to avoid getting into problems during high sink rates. |
| MC16 | MC1 $Z_{\eta_0} = 0.25$ $Z_{\eta_1} = 0$ $T/N = 1.05$ | A-FB | 3.0 | 5 | | Thrust more than adequate for takeoff. Required a little anticipation to stop at desired maneuvering altitude. During air taxi and turn-over-a-spot moderate pilot attention was required to control altitude, but performance was not degraded. | Some tendency to upset altitude, but had more than adequate thrust to arrest the motion. | Adequate thrust and damping for precision hover. During landing sequence had adequate thrust to arrest sink rate and did not have to place any limitation on sink rate for fear of not being able to arrest it. | Only moderately objectionable feature was that it could use a little more height damping. |
| MC17 | MC1 $Z_{\eta_0} = 0.25$ $Z_{\eta_1} = 0.25$ $T/N = 1.05$ | A-FB | 3.0 | 4 | | Not much difficulty in performing constant altitude maneuvers. Altitude required small amount of attention but seemed to have adequate damping and thrust for maintaining constant altitude. | No altitude control problems. | Precision hover performance was very good and required very little pilot concentration. There was adequate thrust for climbing but stopping at desired altitude required some pilot anticipation. | At this damping level thrust seemed adequate, but a little more height damping would be desirable. |
| | | A-FB | 3.0 | 2.5 | | Could perform air taxi with precision and hold altitude quite accurately. Altitude very stable, easy to correct and generally did not stray much from desired altitude. No need to lead inputs. | Could perform this task easily and precisely and could make fairly large altitude changes without affecting height too much. | Could hover very precisely, very little need to monitor altitude. In the landing maneuver could descend quite precisely to 20 ft and come back up. The vertical response was positively good, didn't seem to lack control power and the damping was more than adequate. No difficulty arresting sink rate, so great need to lead altitude inputs. Could land quite precisely. | No real objectionable features to this case. |
| | | A-MS | 3.06 | 2.5 | Selected to get test response in height. | Maneuvering no problem. Could perform the task precisely and had no real problem with holding height during either the longitudinal or lateral maneuvers. | Could perform these precisely. Did see some decrease in altitude when making very abrupt lateral stops with large roll excite, but easily corrected. | Precision hover no problem. In landing sequence could change altitude very abruptly and stop quite precisely with no noticeable overshoot. Could also climb fairly rapidly. | Might like to see a little more control power, but not much. No real objectionable features. |
| MC18 | MC1 $Z_{\eta_0} = Z_{\eta_1} = 0.40$ $T/N = 1.05$ | A-FB | 3.0 | 3.5 | | During takeoff had adequate thrust for climb out. No difficulty stopped at maneuvering altitude of 40 ft. During constant altitude maneuvers altitude required very little effort to control and altitude control was good. Height damping seemed well damped and to have a rate-type response. | No problem with task. | Hovering performance good and required very little effort. Could not develop real high rate of climb or rate of descent due to limitation on thrust and/or high damping. A little more thrust would have been desirable to develop higher rates of climb and to insure arresting sink rate during descent. | Only slightly objectionable feature was perhaps being a little sluggish in response in altitude due to the lack of control power. |
| MC19 | MC1 $Z_{\eta_0} = Z_{\eta_1} = 0.05$ $T/N = 1.10$ | B-MS | 3.24 | 6 | Selected to help in stabilizing height oscillations. | Could maneuver longitudinally without too much trouble, when maneuvering laterally introduced a fairly large longitudinal displacement error while concentrating on height. Height required a lot of pilot compensation to stabilize, was in almost constant oscillation up and down, as much as 20 ft. | Longitudinal quick stops performed fairly well while holding height within 25 to 30 ft. Lateral quick stops quite difficult because of the lack of height damping. | No difficulty hovering. Could keep height oscillations small while hovering accurately. Could perform landing sequence fairly accurately. Could descend relatively quickly to 20 ft and stabilize and rise again to 40 ft, then land gently. Height dynamics definitely affects ability to control other axes (particularly roll). | Height dynamics objectionable, need more damping. |
| MC20 | MC1 $Z_{\eta_0} = Z_{\eta_1} = 0.125$ $T/N = 1.10$ | A-FB | 3.0 | 2.5 | | Had more than adequate thrust for takeoff and had little difficulty stopping at desired altitude following climb out. During the constant altitude maneuvers had to devote only a small amount of attention to the control of altitude. | | Precision hover required very little concentration or control activity. During landing sequence maneuver had no difficulty arresting sink rate, however, small amount of anticipation required to stop at desired altitude. | Only improvement desired might be a slight increase in altitude damping. Otherwise configuration is quite satisfactory. |
| | | A-FB | 3.0 | 4.5 | | In general could perform air taxi relatively well. Did have to pay attention to altitude, however, and make fairly constant corrections. Had to take concentration away from horizontal position a good deal to monitor altitude. Had to lead altitude control somewhat. Would like to see a little more altitude damping. Had adequate control power. | Could perform this maneuver without too much difficulty. Didn't notice a lack of control power and went to relatively large altitudes without affecting altitude too much. Rather occasionally by the time that altitude would tend to change unnoticed. | Hover performed quite accurately, but altitude required attention. Landing sequence performed fairly well. Could maneuver vertically at satisfactory rates, but had to lead inputs somewhat when arresting vertical rates. | Would like to see a little more altitude damping, although it is not all that bad. Think control power is adequate. |

TABLE B-VIII (Continued)

| No. | Ref. Parameters | Alt. Range | Rate | Task | Pilot Comments | | | | |
|------|--|------------|------|------|---|---|---|--|---|
| | | | | | Selection of Reference Configuration | Maneuvering | Quick Stops | Precision Hover, Landing Sequence and Secondary Dynamics | Overall Remarks |
| K220 | SC1 $\dot{z}_0 = \dot{z}_g = 0$ $\dot{z}_g = 0.25$ $\dot{z}_g = 1.10$ | A-7B | 2.62 | 3 | Selected to get desired height control response. | Not too much difficulty with longitudinal maneuvering. In lateral maneuvering noticed some coupling between altitude and roll, had to be kind of careful maneuvering laterally because could build up some fairly substantial height variations if not watched closely. | Had to be careful with lateral roll rate to make sure that height wasn't disturbed. Had to watch height closely, definitely some coupling between roll and height. | No problem, could hold height fairly well, 22 to 3 ft. Could descend to 20 ft and stop rapidly. Some control compensation required, but could stabilize relatively well at desired height and then climb to 40 ft without too much difficulty. | Slight lack of height damping, not seemed to be plenty of thrust. |
| K221 | SC1 $\dot{z}_0 = 0$ $\dot{z}_g = 0.25$ $\dot{z}_g = 1.10$ | A-7B | 3.0 | 4.5 | Selected to get desired height response. | More than adequate thrust for takeoff. Had good rate of climb but had to anticipate desired maneuvering altitude a little. During air taxi and hovering turn maneuver manual performance was fairly good but had to direct moderate attention to control of altitude. | Tended to upset altitude but had adequate thrust margin to arrest sink rates. | Precision hover performance was very good and required very little effort or concentration. No problem arresting sink rates as there was more than adequate thrust and even didn't have too much difficulty stopping at desired altitude. | Only objectionable feature was a slight deficiency in altitude damping, but thrust seemed more than adequate. |
| | | B-7B | 3.0 | 5 | | Altitude tended to wander when maneuvering and when performing quick stops. Had to monitor altitude a good bit in order to hold altitude precisely. Could perform the task fairly well. | Performance fairly good, but altitude needed attention and tended to overshoot periodically when making corrections. | Could hover precisely, had to monitor altitude again, but altitude control not too difficult. The landing sequence was performed fairly well, had some difficulty arresting attitude, some tendency to overshoot desired altitude. | Needs more altitude damping. |
| | | B-7B | 2.50 | 3.5 | | No problem with air taxi. Had to watch height while maneuvering laterally, but could control this to within about 3 ft. | Had to keep attention on height when making lateral quick stops and make some compensating inputs, but height didn't change rapidly. No problem with longitudinal quick stops. | Hover no problem. In landing sequence could change altitude fairly abruptly and stop without too much difficulty. Had to compensate for compensating a little but didn't require too much effort. | Would like to see a little more damping, but the case is relatively easy to control. |
| K222 | SC1 $\dot{z}_0 = 0.75$ $\dot{z}_g = 0$ $\dot{z}_g = 1.10$ | A-7B | 3.0 | 4 | Selected to get desired height response | Good thrust for takeoff and developed good rate of climb, stopping at desired altitude was not too much of a problem. Constant-altitude maneuvers required moderate attention to altitude control but performance was fairly good. | These maneuvers upset altitude the most and required the most attention. | Precision hover performance was very good and required very little effort. Had no difficulty at all arresting sink rates or stopping at desired altitudes. | Only annoying feature seemed to be attention required to control altitude during constant altitude maneuvers. |
| K223 | SC1 $\dot{z}_0 = 0.75$ $\dot{z}_g = 0$ $\dot{z}_g = 1.10$ | B-7B | 2.75 | 3.5 | | No problem with longitudinal maneuvers. Could perform task precisely and hold hover altitude relatively well, 22 to 3 ft. Had to pay somewhat more attention to height during lateral maneuvers. | Could perform fairly well, introduced slightly larger height errors during lateral than longitudinal maneuvers, but height didn't change rapidly and it was reasonably easy to correct. | Hover no problem. Could descend relatively rapidly and arrest descent accurately and quickly. Had to use a few small compensating control inputs but fairly easy to do. | Might like to see a little more height damping, but this is not a bad case. |
| | | A-7B | 3.0 | 7.5 | Selected to get desired height response | More than adequate thrust for takeoff and had no difficulty at all stopping at desired altitude following climb out. Altitude control during all of the constant altitude maneuvers was relatively easy and required very little effort. | No problem. | Precision hover performance was very good and required very little effort. With thrust and height damping seemed adequate. During the landing sequence maneuvers had no difficulty arresting sink rate or stopping at desired altitude. | Good configuration |
| | | B-7B | 3.0 | 4 | | Air taxi could be performed with fair precision, although it would have been aided by a little more altitude damping. Altitude tended to creep away periodically. Altitude control required some feedback. However, most disadvantage factor was that it tended to drift off when attention not paid to it almost constantly. | Could perform this task relatively well. Could go to fairly large attitude angles without having altitude change abruptly, but attitude tended to drift away. | Not difficult, but had to pay attention to altitude. Could change altitude relatively quickly and stop without too much difficulty. Needed to land inputs a little but not a great deal. Landing was precisely. Generally, but no complaint about ability to maneuver vertically, but was bothered by lack of altitude stability. Don't think altitude held any better than about 25 ft or more. | Needs a little more altitude damping. |
| K224 | SC1 $\dot{z}_0 = \dot{z}_g = 0$ $\dot{z}_g = 0.25$ $\dot{z}_g = 1.10$ | A-7B | 3.0 | 2.5 | Selected to get desired height response | Air taxi maneuver and turn-over was spot relatively easy to perform and had relatively good performance. Control of altitude required very little attention. Height seemed adequately damped and to have adequate thrust for control. | Relatively easy to perform. | Precision hover required very little effort and could control all axes quite well. Adequate thrust for climbing and changing altitudes and arresting sink rate. There may have been very small amount of anticipation required to stop aircraft at desired altitude. | Good configuration |
| K225 | SC1 $\dot{z}_0 = \dot{z}_g = 0$ $\dot{z}_g = 0.25$ $\dot{z}_g = 1.10$ | A-7B | 3.0 | 10 | Get range of sensitivity in an attempt to obtain closed-loop control over altitude. | Had an extremely difficult time controlling altitude. It required a/cross anticipation to arrest vertical motion and at times got into violent PIO's that usually resulted in hitting the ground. Found it went to impossible to perform the task because when attention diverted from altitude, altitude control lost altitude control through either pre live-action or PIO tendencies. | | | It is mandatory that this configuration have more height damping. Control would be lost during some portion of the required task. |

TABLE B-VIII (Concluded)

| No. | Ref. No. | Pilot's Note | T ₀ | T ₁ | Pilot Comments | | | | | |
|-----|----------|--|----------------|----------------|------------------------------------|---|--|---|---|---|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Precision Hover, Landing Sequence and Secondary Dynamics | Overall Evaluation | |
| M25 | RC | $Z_{\delta} = Z_{\delta_0} = 0$ T/N=1 | 3.79 | 3.02 | 6 | Selected in an attempt to stabilize height control. | Very difficult to perform because of attention needed to stabilize height. Couldn't perform any maneuvering task precisely because of concern about possible ground strike. Height awareness must have been up to -60 to 70 ft. Very difficult to keep height under control and attempt to perform task. | Very difficult to perform the task with any precision because of very poor height control. | This wasn't quite as bad, could hover fairly well but had some difficulty stabilizing height. The landing sequence was hard to impossible to perform. Couldn't stabilize on either 20 or 40 ft altitudes. The vertical landing also difficult, got close to the ground and then just dropped it in to prevent oscillating case more. | Definitely needs more damping in height; this is completely unacceptable. |
| | | | 3.88 | 3.06 | 6 | Selected in an attempt to gain control of altitude oscillations. | Very difficult to perform. Can't do it with any precision. Must concentrate on altitude control, then this degrades maneuver performance. Altitude control no better than 140 ft. | Had simulator emergency during the lateral quick stop because of the difficulty in controlling altitude. Can't perform any task with precision. | Couldn't hover precisely or hold hovering position while landing. Concerned mainly with height control and stabilizing it to some extent. The landing sequence was a hit and miss operation. Just had to let hovering precision deteriorate and very anxiously get altitude down to 20 ft. Had to land control inputs a great deal. | Difficult to control height -- certainly the most objectionable feature. Extremely difficult to keep height anywhere in bounds. Needs height damping. |
| M26 | RC | $Z_{\delta} = Z_{\delta_0} = 0$ T/N=1 | 4.78 | 2.60 | 5 | Set height control sensitivity for both altitude response and altitude stability. | Controlling altitude requires moderate pilot compensation, that is, required some anticipation to step at desired altitude. Air taxi maneuver required moderate concentration on altitude control. | Required moderate concentration to perform it. | Precision hovering required moderate pilot concentration both to offset mean wind effects on aircraft position and to control altitude. Because of the divided attention it was generally held only within 110 ft of the desired altitude. | Most objectionable feature was the slightly low damping in altitude. Feel more damping would be required to make this a satisfactory configuration. |
| | | | 4.78 | 3.28 | 4.5 | Selected for desired control response in height. | Air taxi not too difficult. Could perform it reasonably well with some precision while holding altitude within about 25 ft. Had to pay a good deal of attention to height, more than desired. | Could perform lateral and longitudinal quick stops with reasonable precision but had to fairly constantly keep attention on height. | Precision hover not too difficult. Could hover precisely, but occasionally altitude would drift off. The landing sequence wasn't too difficult. Would like to see some more height damping, however. Difficult to stabilize and hold altitude precisely. Approached landing cautiously, but performed it OK. | Objectionable feature was primarily the lack of height damping. Would like to see a little more. |
| | | | 4.88 | 2.70 | 4.5 | Height control sensitivity selected to control height oscillations. | Generally could maneuver relatively well, but think that lack of damping in height affected ability to perform maneuver. Could hold height within about 110 ft, but altitude was in constant motion. Couldn't really stabilize on any given altitude particularly well. | No real difference in remarks compared to maneuvering. | Could hover fairly well while holding altitude without too much effort, but hovering position was degraded somewhat. Had to make fairly continuous inputs to height to keep stabilized and to keep within 110 ft. In landing sequence could decrease altitude to about 20 ft fairly well, but every now and then would have to make an abrupt input to control hovering position. | Would like to see a little more damping in height, although this isn't critical. |
| M27 | RC | $Z_{\delta} = Z_{\delta_0} = 0$ T/N=1 | 4.78 | 3.71 | 3 | Selected height control sensitivity for desired altitude response during takeoff and landing. | Air taxi wasn't too difficult, except that relatively large attitude changes were required to initiate and sustain velocity. On 14 hold heading and altitude fairly accurately with only a moderate control effort. | Most objectionable feature of quick stops was the large altitudes required to initiate the translational motion. | Was annoyed somewhat by gust disturbances during precision hover in both position and a little in altitude. This was a mildly unpleasant characteristic. Altitude control required very little activity and seemed to be fairly well damped. | Generally good configuration. |
| M28 | RC | $Z_{\delta} = Z_{\delta_0} = 0$ T/N=1 | 4.78 | 3.82 | 3 | Selected height control sensitivity to get desired response for making altitude changes. | Air taxi was relatively easy to perform because very little attention was required to control altitude. Turn-over-a-spot required pilot effort only because of the mean wind effects on position such that relatively large changes in wing tilt trim were required. | Relatively easy to control. | Precision hover was very easy from the standpoint of controlling altitude, most attention was required to offset drag effects on the airplane. Height control was very good. | Would rate it 2.0, but because of mean wind effects on the aircraft, will rate the overall configuration 3.0. |

TABLE B-IX

PILOT COMMENTS FROM THE STUDIES OF HEIGHT CONTROL SYSTEM LAGS AND DELAYS AND INCREMENTAL THRUST THROUGH STORED ENERGY

Flying Qualities Results Given in Table A-X

| Case | Conf. Parameters | Pilot- In- Use | T ₀ | P ₀ | Pilot Comments | | | | |
|------|--|----------------------|----------------|----------------|--|--|---|---|--|
| | | | | | Reaction of Control Sensitivity | Maneuvering | Quick Stop | Precision Hover, Landing Sequence and Secondary Dynamics | Overall Evaluation |
| K1 | K1 $\tau_{\theta} = \tau_{\phi} = 0.125$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0$ | A-FB | 3.0 | 4.5 | | Takeoff performance quite good, but had to anticipate desired lowering altitude of 40 ft. During air taxi altitude required considerable attention, and altitude deviated more than desired. | Altitude performance was fairly good during turn maneuver, but during quick stop there was considerable variation in altitude. | Hovering performance was fairly good, but had to devote some attention to control of altitude. During landing sequence maneuver had no problem arresting sink rate but required some attention to stabilize altitude. This applied to the landing, too. | Most objectionable feature seemed to be a combination of either light damping in altitude or perhaps lag in the thrust response. |
| | | B-FB | 3.0 | 3.5 | | Altitude required considerable attention and compensation during both the maneuvering and quick stop portion of the task. Could not disregard altitude even for a moment. Had to lead inputs and make fairly continual control inputs. | Considerable pilot effort required. Performance not too good. | Could hover fairly precisely, but had to make relatively continuous altitude control inputs to hover accurately. Could perform landing sequence but had to be very careful about descending too rapidly and overshooting desired altitude. Same applied to ascending. Had to anticipate desired altitude. Couldn't land smoothly because of thrust lag. | Altitude needs more damping or lower thrust lag. |
| | | B-HB | 3.01 | 3 | Selected to get desired height response. | So difficult performing air taxi while holding height within fairly close tolerance, say about 25 ft. Height seemed to be relatively stable, fairly well damped and didn't change abruptly when performing the lateral maneuver. | No problem holding height during the longitudinal quick stop; during the lateral quick stop developed some attitude angles which were large enough to introduce height errors and caused some difficulty in height control, but really nothing extreme. | No problem, could hover quite accurately and hold height very steady. In landing sequence could descend at fairly rapid rates and stop quite precisely. No oscillations evident. Could land carefully, had no worries about oscillating in height near the ground. | Don't find anything too objectionable with height, it seems to be relatively easy to control. Think the motion helped in controlling altitude. |
| K2 | K2 $\tau_{\theta} = \tau_{\phi} = 0.175$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0.1$ | A-FB | 3.0 | 2.5 | | Very good takeoff performance, but no difficulty stopping at and holding 40-ft altitude during constant altitude maneuver. In fact, very few control inputs were required while performing air taxi, quick stop and turn-over-a-point maneuver. | | Thrust response seemed fairly good when arresting sink rate during the landing sequence maneuver and stopping at the 20-ft altitude. Thrust control was also adequate for landing. | Good altitude control. |
| K3 | K3 $\tau_{\theta} = \tau_{\phi} = 0.175$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0$ | A-FB | 3.0 | 3 | | Climb out performance was good and had no problem stopping at desired altitude. Very little effort required to hold altitude while performing the air taxi, turn-over-a-point, and quick stop maneuvers. | | Hovering performance was very good and required very little effort to control altitude. There was either a slight limitation or delay in thrust when attempting to arrest sink rate, but this was no particular problem. | Only objectionable feature was the slight limit or delay in thrust when arresting sink rate. |
| | | B-FB | 3.0 | 3 | | Air taxi and quick stop maneuvers could be performed while holding altitude relatively constant. Altitude not difficult to maintain during these maneuvers. Tendency to overshoot but not too rapidly, easily compensated. | | Hover could be performed quite precisely while holding altitude within very close tolerance of about 25 ft. The landing sequence also was not difficult to perform. Some small tendency to overshoot when descending and ascending but easy to compensate. | Would probably like to see a little more damping and a little less lag, but in general is not a bad height-control configuration. |
| K4 | K4 $\tau_{\theta} = \tau_{\phi} = 0.175$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0.1$ | A-FB | 3.0 | 3.5 | | Climb out was satisfactory following takeoff and had no difficulty stopping at maneuvering altitude of 40 ft. Altitude control required very little attention while performing air taxi, quick stop and turn-over-a-point maneuvers. | | Altitude control during precision hover was very good. During landing sequence did notice a little lag in thrust response in trying to arrest sink rate, so had to anticipate desired altitude. Again, during climb out thrust was adequate but noticed a slight lag in thrust response while performing the final landing. | A slightly objectionable feature seemed to be a small lag in thrust when attempting to land or arrest sink rate. |
| K5 | K5 $\tau_{\theta} = \tau_{\phi} = 0.175$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0$ | A-FB | 3.0 | 4.5 | | Had adequate thrust for takeoff and climb out to desired altitude. Only small amount of effort required to stabilize at desired altitude. During constant altitude maneuvers had to give some attention to controlling altitude as there was some tendency to oscillate about desired maneuvering altitude of 40 ft. | Required a little more altitude control but this was not a particular problem. | During precision hover noticed tendency to oscillate and hunt in altitude slightly, but in general performance was fairly good. During landing sequence noticed a lag in thrust when attempting to arrest sink rate, but this was only a moderate problem. Thrust response was slightly slow during landing. | Most objectionable feature seemed to be a slight lag or delay in thrust response when attempting to arrest sink rate. |
| | | B-FB | 3.0 | 3.5 | | Generally could perform air taxi precisely and hold altitude fairly constant. Some small tendency for altitude to drift off but this was relatively easily corrected. Had to pay some attention to altitude but really it didn't tend to get away. | Could be performed with precision and without abrupt changes in altitude. Had to monitor altitude. | Precision hover could be performed easily and altitude prevented no great problem. Could descend and ascend without too much difficulty. Did have to lead inputs, however, has to be concerned about overshoot, especially when ascending altitude. Vertical landing could be performed quite precisely, but had to be careful in arresting sink rate. | Some thrust lag effects evident. Might like to see a little more damping, but this is not a particularly bad case. |
| K6 | K6 $\tau_{\theta} = 0$ $\tau_{\phi} = 0.35$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0.6$ $\tau_{\delta} = 0$ | B-FB | 3.0 | 4 | | Air taxi no great difficulty. Some coupling between height and roll motion but didn't have to make particularly large or rapid inputs to correct for it. Everything pretty relaxed. | No difficulty, could hold altitude fairly well even while performing the lateral quick stop, but again there was some coupling noticeable there. | Hover no difficulty. Could hold both longitudinal and vertical position quite well. Landing sequence was a little touchy, had to be careful not to build up descent rates which were too large because of a tendency to develop some oscillations in height. Had to avoid abrupt inputs though. | Objectionable feature was slight oscillatory tendency in height, although this wasn't a problem. |
| K7 | K7 $\tau_{\theta} = 0.25$ $\tau_{\phi} = 0.25$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0$ $\tau_{\delta} = 0$ | A-FB | 3.0 | 2.5 | | Good climb-out performance following takeoff. Very little altitude control was required. | These maneuvers induced some altitude error, however, control was relatively easy. | Virtually no altitude control was used during the precision hover. There was adequate thrust and damping during the landing sequence maneuver and any thrust lag was not noticeable. | Good altitude control. |
| K8 | K8 $\tau_{\theta} = 0$ $\tau_{\phi} = 0.35$ $\tau_{\psi} = 0.05$ $\tau_{\delta} = 0$ $\tau_{\delta} = 0$ | B-HB | 2.67 | 4 | Selected to get desired height response. | Not difficult. Could maneuver accurately while holding height relatively well. Height tended to increase during the lateral maneuver, however. | Couldn't control altitude precisely during lateral quick stop. | Hover not difficult. Would prefer more thrust for arresting my rate of descent. Can't climb either in lift or thrust. | Moderate lack of thrust |

TABLE B-IX (Concluded)

| No. | Test Parameter | Altitude (ft.) | Rate (ft./sec.) | Time (sec.) | Flight Comments | | | | |
|-----|---|----------------|-----------------|-------------|---|--|--|---|--|
| | | | | | Selection of Control Sensitivity | Maneuvering | Quick Stops | Precision Hover, Landing Sequence and Secondary Dynamics | Remarks |
| 102 | W1 $Z_0 = 0$ $Z_0 = -0.35$ $T/N = 1.02$ $ST/N = 0.13$ $T_0 = 0.10$ | 4-PS | 3.0 | 1 | | Height control required attention. No abrupt changes in altitude but tended to drift off. Had to lead collective inputs and avoid building up large descent rates. | Developed height errors of 25 ft. | Hover not too difficult. Could hold altitude precisely. Moderately difficult to arrest my descent at 20 ft and stabilize altitude there, lack of available thrust. Could land safely, however. | Could have installed thrust-to-weight ratio and possibly more damping. |
| 103 | W1 $Z_0 = 0$ $Z_0 = -0.35$ $T/N = 1.02$ $ST/N = 0.13$ $T_0 = 0.2$ | 4-PS | 3.0 | 3 | | Height control required some attention but only low frequency corrections needed. Didn't have to lead inputs much. | Height control not difficult. | Could hover precisely with only small variations in altitude. Relatively easy to perform landing sequence. Could build up appreciable altitude rates, maintain them, and arrest height changes quickly. | |
| | | 4-PS | 2.65 | 3.5 | Selected to get desired rate of height change. | No problem either laterally or longitudinally. Could maneuver and stop precisely. No difficulty holding altitude quite precisely. | No problem even in lateral quick stops. Could stop abruptly and hold altitude quite precisely. | Hover no problem. Generally could handle landing sequence fairly well. A little concerned with ability to stop rate of descent. At times overrode altitude a little, so had to descend with some care. Think thrust is adequate. | Objectable feature - A slight objection to lack of thrust that was evident when trying to stop fairly high descent rates. |
| 104 | W1 $Z_0 = 0$ $Z_0 = -0.35$ $T/N = 1.02$ $ST/N = 0.20$ $T_0 = 0.10$ | 4-PS | 3.0 | 3.5 | | Altitude required attention when maneuvering. However, generally could control it fairly well. Some tendency to creep off as I increase altitude but it happened relatively slowly. Could build up fairly significant rates and arrest them without too much difficulty. | Required some attention, but could control altitude fairly well. | Hover no problem. Could perform this precisely and hold altitude quite accurately. The landing sequence also not too difficult. Could go down to 20 ft at a relatively rapid rate and arrest altitude without too much difficulty. Did have some problems stabilizing it but nothing too significant. | Fairly good case. |
| | | 4-PS | 2.07 | 3 | Selected to get desired response in height and desired rate of change of altitude for a comfortable control input | Generally no problems with air test. Could maneuver precisely and hold altitude accurately. | Performed quick stops precisely and had no problem holding height. | Hover was not difficult. Some lack of thrust when arresting descent. Concerned with building up too large a descent rate, however, seemed to be able to arrest as rapidly as desired. Seemed to have adequate thrust available. | Objectable feature was the slight lack of thrust when descending. A little concerned with inability to arrest descent rates, but with care can keep them well under control. |
| 105 | W1 $Z_0 = 0$ $Z_0 = -0.35$ $T/N = 1.02$ $ST/N = 0.25$ $T_0 = 0.05$ | 4-PS | 3.0 | 3.5 | | During maneuver had to watch altitude reasonably closely. Tended to increase slightly, but didn't seem to be difficult to control and it was reasonably predictable. Don't recall having to lead inputs too greatly. | No problem with altitude control. | Could hover precisely and hold altitude closely. Landing sequence was not difficult to perform. Could hover precisely and descend to the 20 ft altitude with no difficulty. Didn't seem to have any real problems arresting descent rates. | Couldn't let descent rates build up too large but for normal descent could arrest altitude precisely. |
| | | 4-PS | 2.07 | 4 | Selected to get desired altitude response. | Air test not difficult. Height control didn't affect ability to control longitudinal or lateral motion while maneuvering. Had a little difficulty holding altitude. Would drift up and down about 15 ft or so. | Could stop quickly and precisely, at least longitudinally, without having altitude change too much. Did lose some altitude during the lateral quick stop. May have lacked a little thrust to recover altitude. | Hover not difficult. Did to be a little careful about rate of descent. Couldn't descend rapidly and stop abruptly. Had to slow down relatively early. | Objectable feature - slight lack of thrust during descent and when trying to recover height during lateral quick stops. |

TABLE B-X (Continued)

| Case | Cof. Parameters | Pilot- Sim. Mode | β_{ref} | IR | Pilot Comments | | | | | |
|------|--|------------------|----------------------|-----|--|--|--|---|--|--|
| | | | | | Selection of Control Sensitivity | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| 06 | K1 $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ | B-FB | 0.270 | 3.5 | Selected to get desired heading rate of change. | No problem. Relatively easy to hold heading. Had to make some corrective heading inputs when maneuvering laterally but heading was well damped. Didn't develop any heading oscillations. | No difficulty in performing these tests. Some corrective inputs required when maneuvering laterally, but could make a good sharp lateral quick stop. | Relatively easy to set up and hold a heading rate and stop precisely at any heading. Wing tilt control was used a small extent. | Hover not difficult. No interaction between heading dynamics and control of other axes. | No objectionable features, this is a good case. Heading is well damped, no evident lags. |
| 07 | K1 $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ | A-FB | 0.273 | 4.5 | Set to maintain directional control in presence of gusts and lags in the directional control. | Performance fairly good, but had some difficulty controlling heading during lateral maneuvers due to gust effects and directional coupling to lateral speed. | Only difficulty was associated with heading control during changes in lateral velocity. | Heading was very responsive to pedals but required anticipation to stop at desired heading due to lags in directional control. Used a small amount of wing tilt control. | Hover performance good but did require attention on direction. | Not objectionable features were related to slightly low damping in direction, gust effects on direction and lag in response to directional control inputs. |
| | | B-FB | 0.181 | 5 | Selected to control heading oscillations, especially when trying to hold heading precisely during maneuver or over. | Ability to maneuver was affected by difficulty in holding heading. Heading tended to oscillate 25 deg almost constantly. Heading was never really stable. Lateral maneuver especially difficult. | Could perform these tests, but heading required a fair amount of attention. Difficult to control height because of attention required for heading. | Could turn over the spot fairly precisely. Didn't seem to get late heading oscillations. Wing tilt control used to some extent. | Had some difficulty hovering because of heading control. Vertical landing could be performed alright heading did affect ability to control in other axes. | Objectionable features the lack of damping in heading and/or the lags. |
| | | B-HB | 0.259 | 4.5 | Selected to get heading rate responses and also to control heading oscillations. | In lateral maneuver had a tendency to develop heading errors and oscillations. Oscillations generally were low level and not too difficult to control, but annoying. | In lateral quick stops had to watch heading fairly closely and make corrections which could develop into oscillations. | If performed slowly could turn and stop precisely, but if heading rates built up and tried to arrest heading abruptly, tended to develop significant heading oscillations. Difficult to damp. | Hover and landing no problem. Think heading affected ability to control roll and lateral motion. | Objectionable features - Don't like the oscillatory characteristics in heading. The lag is apparently present. |
| 08 | K1 $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ | A-FB | 0.200 | 5.5 | Selected to get desired turn rate for heading control. | Found it difficult to stabilize heading when maneuvering laterally. Built up fairly significant oscillations in heading (about 210 to 215 deg) that affected ability to perform lateral maneuver. | Only lateral quick stop was difficult. Ability to perform quick stop affected by the heading control difficulty. | Could develop and hold turn rate fairly well, but had difficulty stopping on desired heading and stabilizing it. Wing tilt control used to some small extent. | No problem with hover. Had to be light on the controls to keep heading oscillations relatively small. Landing no difficulty. Heading control did slightly affected ability to perform lateral maneuver. | Heading control objectionable, the lags are simply too large. Tended to develop oscillations. |
| | | B-HB | 0.226 | 5 | Selected to control heading oscillations. | Developed heading oscillations when maneuvering both laterally and longitudinally. Somewhat difficult to control heading. Tends to stay away, very oscillatory. | Especially during lateral quick stops heading was oscillatory and required significant amount of attention. | Had to be careful not to slide by desired heading. Very easy to do with this case. | Hover and vertical landing not difficult. Heading control affected ability to control pitch, roll and to some extent height. Took attention away from these other axes. | Objectionable features lack of damping and lag in heading control. |
| | | A-FB | 0.215 | 5 | Set for desired response while making heading changes. | Relatively easy except lateral maneuver required attention to maintain heading. Performance relatively good however. | Required a little more attention on heading. | Performance fairly good although couldn't maintain a constant turn rate very accurately. Required a little anticipation to stop at desired heading and some difficulty stabilizing it. | Precision hover and landing performance good and required very little effort. | Only objectionable feature was that directional damping was slightly low. |
| 09 | K1 $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ | B-FB | 0.232 | 6 | Selected to get desired turn rate for an acceptable pedal input and also in an attempt to hold control heading oscillations. | Performance affected by lack of damping and lags in heading. Tended to develop fairly constant heading oscillations during maneuver. This was more pronounced while maneuvering laterally. | Ability to perform this test was also affected by the lack of damping in heading. | Could turn fairly well and control turn rate without much difficulty, but it was tough to hold a heading. Wing tilt used a little. | While hovering was oscillating in heading. Could hover fairly well, but at times hover position was affected by attention being directed to heading. Had to watch heading while landing. Lack of damping and lag in heading affected ability to control roll pitch and height. | Needs some more damping in heading or reduction in lags. Almost impossible to damp out heading oscillations; ability to control other axes is affected. |
| 200 | K1 $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ | B-FB | 0.248 | 6 | Selected to get turn rate desired for a given pedal input. | Could perform the longitudinal maneuver relatively well, but lateral maneuver was more difficult. Had to be very careful to avoid exciting heading oscillations. Could not control heading too tightly. Very definite tendency to build up PIO's in heading. | Difficult to perform. Had to be careful about heading control. | Not too difficult, but it was tough to stop on a given angle precisely. Tendency to oscillate to fairly large heading angles. | Could perform hover and landing fairly well, but heading did tend to wander. Very definite lack of damping, the lags in heading affect ability to control pitch and especially roll. | The PIO tendency in heading due to lags and delays are objectionable. All cases with large lags are somewhat unusual in that if control inputs kept small they aren't that bad, but once one develops large oscillations so quickly that they must be regarded as undesirable. |
| 011 | K1 $\beta_{\text{ref}}=1.0$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ $\beta_{\text{ref}}=0.5$ | B-FB | 0.306 | 3 | Selected to get the desired turn rate. | Could perform this maneuver quite well, heading control no problem. Noticed some very slight oscillations in heading, but not difficult to control. | Noticed some slight oscillatory tendency in heading, very, very slight, easily correctable. | Could turn precisely, select turn rate desired without too much trouble. Wing tilt control used a little to correct the effects of nose wind. | No problems. Some slight tendency to oscillate both forward and backward but didn't affect ability to hover or land precisely. | No real objectionable features. Slight tendency for heading to oscillate, but not difficult to control. |

TABLE B-X (Continued)

| Case | Cof. Parameters | Pilot-Dir. Rate | τ_{θ} | FF | Pilot Comments | | | | | |
|------|---|-----------------|-----------------|-----|---|---|--|---|---|---|
| | | | | | Selection of Control Sensitivities | Maneuvering | Quick Stops | Turn-Over-a-Spot | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| D12 | RC1 $\tau_{\theta}=1.0$ $\tau_{\phi}=0.5$ $\tau_{\psi}=0.1$ $\tau_{\dot{\psi}}=0.1$ | A-FB | 0.294 | 2 | Selected to get desired turn rate response to pedal inputs. | Could perform both lateral and longitudinal maneuvers precisely while paying very little attention to heading control. Heading quite stable, no tendency toward oscillations. | No difficulty. | Could turn quite precisely, stop abruptly and remain there without oscillation. Heading control no problem. | Could hover quite accurately, hold position well without having to vary about heading. | No objectionable features. All axes well damped. Comfortable aircraft to fly. |
| D13 | RC1 $\tau_{\theta}=1.0$ $\tau_{\phi}=0.5$ $\tau_{\psi}=0.3$ $\tau_{\dot{\psi}}=0.1$ | A-FB | 0.291 | 3 | Set for desired heading response. | During air taxi heading response was relatively easy and quiet efforts and coupling to lateral velocity were rather minimal. | Required some attention to control heading due to lateral velocity coupling during the lateral quick stop maneuvers. | May be maintain a constant turn rate and to stop at desired heading. We have noticed a very slight lag in directional response but because of the relatively slow control in direction this was of no particular problem. | Hover and landing no problem. | Good directional control characteristics. |
| | | A-FB | 0.213 | 4 | Selected to get desired turn rate response to pedal inputs. | Could perform task fairly well. Anxious at times by the slight oscillation that built up in heading, say 15 deg. Seemed to write it more often when maneuvering laterally, required some attention to damp it. | Could perform the quick stops rather well but at times had some problems with the heading oscillations. | Could perform task quite well. Could turn at desired rate, stop precisely, and hold heading without too much trouble. Remained over the spot fairly well. | Could hover quite accurately and land without too much trouble. Some interaction between the heading control requirements and ability to control other axes. | Slight oscillation that built up in heading periodically was probably the only objectionable feature in heading. |
| | | A-HB | 0.279 | 3.5 | Selected to get desired turn rates. | No problem either laterally or longitudinally. Laterally did develop some small heading motion but no real oscillations and easily controlled. | No problem longitudinally. Laterally had to watch heading a little but it was quite easy to stabilize. | No real problem stabilizing heading after the turn. | Precision hover and vertical landing not difficult. Heading control did not affect other axes. | No significant objectionable features. Heading a little oscillatory. |
| D14 | RC1 $\tau_{\theta}=1.0$ $\tau_{\phi}=0.5$ $\tau_{\psi}=0.3$ $\tau_{\dot{\psi}}=0.1$ | A-FB | 0.250 | 3 | Set for desired heading response to pedal inputs. | Relatively effortless but had to give a little attention to heading control during lateral maneuvers. Dist effects on direction were minimal. | Task posed no particular problems. | Turn rate control quite good and could stop at desired heading with relatively little anticipation. Held relatively little wing tilt control. | Performance was good and required very little effort. | Slightly annoying characteristics here were slight gust effects and control lag in heading, however, only slightly noticeable and little attention required. |
| | | A-FB | 0.309 | 4.5 | Selected to get desired rate of heading change. | Task not difficult longitudinally; laterally had some difficulty holding heading and developed heading oscillations that at times affected ability control lateral displacement. | Lateral quick stops required attention in heading; feel performance degraded by lags in heading control. | Could hold and develop a turn rate fairly well but tended to develop some oscillations after attempting to arrest the heading. Wing tilt control was used a little. | Hover and landing presented no problems. Heading dynamics did affect ability to control laterally somewhat. | Objectionable feature was the lag in heading, although it could have been worse. |
| | | A-HB | 0.270 | 3.5 | Selected to get desired turn rates. | Noticed some slight heading oscillations for both lateral and longitudinal maneuvers, but in general could control them while paying only moderate attention. | Heading oscillations were evident for both lateral and longitudinal quick stops, but it was not particularly difficult to control. Possibly ability to perform the task was degraded slightly due to attention devoted to heading. | Not too difficult, some tendency to slide by desired heading and then develop oscillations when attempting to recover. | Precision hover and vertical landing not difficult. Heading dynamics did affect ability to control pitch and roll to some small extent. | Would like more damping or less lag in heading. |
| D15 | RC1 $\tau_{\theta}=1.0$ $\tau_{\phi}=0.5$ $\tau_{\psi}=0.6$ $\tau_{\dot{\psi}}=0.1$ | A-FB | 0.271 | 4 | Set to get desired heading response. | Had to give some attention to directional control, especially during lateral maneuver due to some gust effects and due to directional coupling to lateral velocity. | During the lateral transition had to give some attention to heading control. | Turn rate control wasn't quite as good as desired and it required a little anticipation to stop at desired heading. Lags were not particularly noticeable. | Hover performance was good, only direction required a small amount of attention. | Most objectionable feature seemed to be a slight deficiency in damping in direction needed to suppress gust disturbances and minimize disturbances due to lateral maneuvering velocity. |
| | | A-FB | 0.237 | 5 | Selected to control somewhat unstable heading when attempting to hold it closely, used reduced value so that wouldn't write action. | Could be performed, but heading affected precision, this was especially true when maneuvering laterally. Couldn't keep from exhibiting heading oscillations which were about 210 deg. | Too much attention necessary for heading control to keep it free oscillating. | Could perform task alright. Turn was performed relatively slowly but quite accurately. Wing tilt control was used. | Could hover fairly well, didn't have too much difficulty holding heading in hover and landing. Heading dynamics affected ability to control during lateral maneuvers and quick stops. | Objectionable features were lack of heading damping and/or the lags in heading. |
| | | A-HB | 0.250 | 5 | Selected to get turn rates and also to help in controlling heading oscillations. | During lateral maneuvers had to watch heading but didn't seem to get into any large oscillations. Some annoyance since lag, so pay more attention to it than desired. | Had to watch heading in lateral quick stop. Possible to get into fairly substantial oscillations in heading. | Approached turns very carefully. Didn't want to develop large oscillations which could happen if rapid turn attempted. | Precision hover and vertical landing no problem. Heading dynamics affected ability to control somewhat. | The lag in heading control which led to heading oscillations during the turn and lateral maneuvers was objectionable. |
| D16 | RC1 $\tau_{\theta}=1.0$ $\tau_{\phi}=0.5$ $\tau_{\psi}=0.6$ $\tau_{\dot{\psi}}=0.1$ | A-FB | 0.308 | 4 | Selected to stabilize heading control. | Had some trouble during lateral maneuvers holding heading and at times almost had a PIO-type situation in uncontrolled heading. Heading was disturbed to some extent by gusts and by the coupling with lateral velocity. Had some difficulty reestablishing and holding heading without overshooting the desired heading. | Had heading control problems similar to those in air taxi. | Wasn't too difficult, but it required some anticipation to stop at desired heading. Very little wing tilt control used. | Hover wasn't too bad, although had to provide some concentration on heading to hold within 25 deg. | Greatest problem was commanding and holding air taxi heading. Seemed to be some lag in the response and at times almost got into a PIO-type situation. |

TABLE B-X (Continued)

| Case | Test Parameters | Pilot, Sig. mode | β_{eff} | PM | Pilot Comments | | | | | Overall Evaluation |
|------|--|------------------|----------------------|-----|---|--|---|--|---|---|
| | | | | | Collection of Control Sensitivities | Maneuvering | Quick Stops | Turn-Over-aspect | Precision Hover, Vertical Landing, Secondary Dynamics | |
| 216 | RCI $\beta_{\text{eff}}=1.0$ $\beta_{\text{eff}}=0.6$ $\beta_{\text{eff}}=0.1$ | A-79 | 0.300 | 5.5 | Selected to get desired turn rate response. | Had some difficulty stabilizing heading. Heading would tend to oscillate through fairly large angular excursions, 110 to 15 deg. during lateral maneuvers. Had to keep pedal inputs as small as possible. | Lateral quick stops did present somewhat of a problem. Had to watch heading slightly and keep correcting it as it tended to oscillate some. | Could turn over the spot fairly accurately and stop fairly well. Kind of difficult to hold turn rate; rate would tend to build up and then taper off. | Precision hover and vertical landing presented no problem. Large lag in heading affected ability to control laterally. | The oscillatory characteristic in heading and the lag in response was objectionable. |
| | | A-82 | 0.264 | 4.5 | Selected to get desired turn rates. | As real problem. Could perform both laterally and longitudinally without difficulty. Had to watch heading a little during the lateral maneuvers and correct for some heading excursions. | Again no problem. Had to correct for heading changes during lateral maneuvers but not difficult. | Could turn precisely and stop fairly quickly. Every now and then developed a small oscillation but not difficult. | Precision hover and vertical landing no problem. Heading control didn't affect ability to control other axes. | Objectionable features: small oscillatory tendency in heading. |
| 217 | RCI $\beta_{\text{eff}}=0.5$ $\beta_{\text{eff}}=0.10$ $\beta_{\text{eff}}=0$ $\beta_{\text{eff}}=0$ | A-79 | 0.238 | 6 | Selected to get desired turn rate at a given pedal input. | Laterally ran into difficulties. Didn't have enough control power to counteract the effects of β_{eff} when maneuvering laterally; this was bad to oscillations. Had to be very careful to keep heading as close to zero as possible because if a yaw error developed there was no way to get heading back during maneuver. | Same situation during the lateral quick stops and once got into some moderate oscillations during the lateral quick stop. | Not difficult. At a low turn rate was stop precisely and hold heading relatively well. With still control and to a small extent. | No problem with heading during hover or landing. The lack of control power in heading coupled with the low damping affected ability to control roll and lateral position. | The lack of directional control power and damping in the primary objectionable feature. |
| 218 | RCI $\beta_{\text{eff}}=0.3$ $\beta_{\text{eff}}=0.13$ $\beta_{\text{eff}}=0$ $\beta_{\text{eff}}=0$ | A-79 | 0.238 | 4 | Selected to get desired turn rate response. | Not difficult at all. Laterally somewhat more difficult as could introduce some relatively small heading oscillations. Reduced a little when maneuvering laterally by the lack of control power and damping, but in general could perform these tasks without much difficulty. | Could perform the lateral quick stop fairly precisely. Not make a large bank angle change to stop abruptly, but had to watch heading somewhat. | Not difficult except had to avoid building up turn rates which were too large, otherwise would overshoot desired heading. | Hover and vertical landing no difficulty. Some rison interaction between heading dynamics and roll control, lateral position control. | Control power is just marginal, would like to see a little more damping in heading, but the case is not too difficult. |
| 219 | RCI $\beta_{\text{eff}}=0.3$ $\beta_{\text{eff}}=0.16$ $\beta_{\text{eff}}=0$ $\beta_{\text{eff}}=0$ | A-79 | 0.238 | 3.5 | Selected to get desired turn rate. | Really no great difficulty in performing air taxi. Some oscillatory characteristics in heading during lateral maneuvers, but easily controlled. | Could perform reasonably precisely, but again some oscillatory characteristics in heading when trying to perform the lateral quick stop. | Generally not difficult, but must avoid building up high turn rates so as to not overshoot heading and go into oscillations. | Hover and vertical landing no problem. Lack of damping in heading had minor effect on ability to control laterally. | Would like to see a little more damping in heading, but the case is not too bad. |
| 220 | RCI $\beta_{\text{eff}}=1.0$ $\beta_{\text{eff}}=0.10$ $\beta_{\text{eff}}=0$ $\beta_{\text{eff}}=0$ | A-79 | 0.708 | 5 | Set for desired directional response. | Performance fairly good and noticed no deficiencies in control power or damping. | noticed a little lack of directional control power when maneuvering laterally while trying to hold heading. | Could not turn at a very high rate due to inadequate directional control power. Practically slowed to a stop when 90 deg to the wind. Had to anticipate desired heading because of insufficient control power. | Precision hover performance was good and there were no deficiencies. | Most objectionable feature was the insufficient directional control power. Could perform the task but it required some additional concentration and workload. |
| | | A-79 | 0.306 | 3.5 | Selected to get desired turn rate response. | Ran out of control power during lateral maneuvers, couldn't counteract the effect of β_{eff} in lateral maneuver to turn the nose related to the turn and couldn't bring it back. | No problem longitudinally, but developed some heading oscillations during the lateral quick stop because of deficiency in control power. | Could perform this relatively well, but could not turn particularly fast. Had to be careful to turn slowly to avoid overshooting desired heading. | No problem with hover and landing. The lack of heading control power did affect ability to control laterally during lateral quick stop and during the lateral maneuver. | The lack of directional control power was objectionable, really seemed some more to perform the tasks adequately. |
| | | A-80 | 0.273 | 7 | Selected to get desired turn rates. | Longitudinal maneuver no problem. In lateral maneuvers tended to run out of control power when large turn rates built up. Affects ability to hold heading. | Generally not difficult, some tendency to develop larger than desirable heading angles when maneuvering laterally. | Difficult to control heading. Could overshoot turn rate, but when at 90 deg to the same wind it was difficult to stabilize heading. Had more control power. | These tasks not difficult. Lack of directional control power definitely affected ability to control pitch and roll. | Lack of control power in heading was very objectionable. |
| 221 | RCI $\beta_{\text{eff}}=1.3$ $\beta_{\text{eff}}=0.13$ $\beta_{\text{eff}}=0$ $\beta_{\text{eff}}=0$ | A-79 | 0.236 | 3 | Set for desired directional response. | Directional heading was good and had no problem performing the air taxi in hover or holding heading during a turn maneuver. | Quick stop maneuvers no problem. | Had good rate control, however, when 90 deg to the same wind noticed a lack of control power as relatively slow turn rate didn't degrade performance and only slightly noticeable. | Hover performance good and directional control quite adequate. | Only slightly objectionable feature was a noticeable reduction in directional control power when 90 deg to the same wind. |
| | | A-79 | 0.370 | 3.5 | Selected to get turn rates that were desirable. | Could perform without difficulty. Had to be somewhat careful to avoid developing large heading rates. As long as directional inputs were moderate, could counter quite well, but noticed the lack of control power every now and then when heading rates got a little large. | Could perform these tasks quite well, both lateral and longitudinal. | Not difficult, but had to avoid developing turn rates which were too large. If turn too rapid would overshoot and it would be difficult to get heading under control again. With small turn rates no problem. | Hover and landing no problem. No noticeable interaction of heading with roll and pitch. | Just a slight lack of yaw control power. Would like to see a little more in case of large heading rates or an emergency. |
| | | A-80 | 0.274 | 2.5 | Selected to get desired turn rates. | Is problem with lateral or longitudinal maneuvers. No apparent absence of control power. | Could perform these maneuvers fairly precisely. No loss of control power evident. Had to be concerned to a limited extent with heading, but it was well damped. | Not difficult, could turn rapidly, stop precisely. Again no evidence of a lack of control power even when 90 deg to the same wind. | No difficulty with hover and landing. No interaction of heading with other axes. | No real objectionable features. Good observation of heading in heading. |

TABLE B-X (Concluded)

| Case | Control Parameters | Sim. Mode | λ_{eff} | N | Pilot Comments | | | | | |
|------|---|-----------|------------------------|-----|--|---|---|--|---|--|
| | | | | | Selection of Control Sensitivities | Maneuvering | Out-a-Steps | Turn-Over-a-Step | Precision Hover, Vertical Landing, Secondary Dynamics | Overall Evaluation |
| DEE | $\lambda_{\text{eff}} = 1.0$ $\lambda_{\text{eff}} = 0.15$ $\lambda_{\text{eff}} = 0$ $\lambda_{\text{eff}} = 0$ | A-FB | 0.097 | 1 | Set for desired response to pedal inputs. | Good control during air taxi; only slight attention required to control heading during the lateral maneuver. Good damping and adequate control power about all axes. | No particular problems, but lateral quick stop required some attention. | Turn rate could be half while accurately and there was no problem in stopping at desired heading. Adequate directional control power to control some wind effects. | Hover performance was very good and required very little attention. | Noticed no deficiency in control power and could perform the tasks quite well. |
| | | B-FB | 0.305 | 2 | Selected for desired heading response for turns. | No problem laterally or longitudinally. Could perform these tasks precisely and didn't have to compensate much for heading changes. Heading quite stable, not affected much at all during lateral maneuvers. Plenty of control power. | Same type of comments as for maneuvering. | No problem, could turn precisely and rapidly and still stop accurately. Wing tilt control used to a small extent. | Not at all difficult to hover and land, could perform these tasks precisely and they weren't at all affected by the heading dynamics. | No objectionable features. Good case. |
| | | E-ND | 0.296 | 2.5 | Selected to get desired turn rate response. | Lateral and longitudinal maneuvers no problem. Will depend. Fine heading control, no indication of a lack of control power. | No problem. Could perform the lateral quick stop precisely, small compensatory inputs in heading. | Also to pedaling, e.g. turn rapidly, stop precisely. | Precision hover and vertical landing not difficult. No interference among the dynamics. | No objectionable features. Good case. |

APPENDIX C

SUMMARY OF CONTROL-POWER-USAGE DATA

Control-power-usage data, which generally consist of the control power levels exceeded five percent of the time, are listed in this Appendix. For some of the studies concerned with control-power limits, the percent times that the control power command exceeded these limits are also presented. Data are shown in this Appendix only for selected test cases, i.e., the exceedance computations were not performed on all the cases considered in the UARL program.

The control-power-usage data tables also generally parallel the tables in Appendices A and B. Control-moment data from the longitudinal and lateral control studies are summarized in Tables C-I through C-VI as follows: C-I, turbulence effects; C-II, control lags and delays; C-III, control-moment limits; C-IV, inter-axis motion coupling; C-V, independent thrust-vector control; and C-VI, rate-command/attitude-hold control. Thrust-usage data from the height control study are presented in Table C-VII. Results from the studies of the interactive effects of height velocity damping and thrust-to-weight ratio and thrust lags and delays are shown there. Control-moment-usage data from the directional control studies are contained in the last table, C-VIII.

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TABLE C-I

PITCH, ROLL AND YAW CONTROL-MOMENT LEVELS EXCEEDED 5 PERCENT
OF THE TIME FROM THE STUDY OF TURBULENCE INTENSITY

Vertical and Directional Parameters Listed in Table A-I
See End of Table for Explanation of Notes

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Turbu- lence, $\sigma_u = \sigma_v$ | Sub- task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|-------|---------------|--------------------|---|---------------------------|------------|-----------|-----------------|-----------|-----------|-----------|-----------------|-----------|-------------|-----------|-----------------|-----------|
| | | | | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | $M_{\dot{\delta}}$ | X_u | $M_{\dot{q}}$ | $M_{\dot{\theta}}$ | | | M_{c_5} | L_{c_5} | $\sin^2 \theta$ | M_{c_5} | M_{c_5} | L_{c_5} | $\sin^2 \theta$ | M_{c_5} | M_{c_5} | L_{c_5} | $\sin^2 \theta$ | M_{c_5} |
| T1 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 3.4 | XM | 0.33 | | 0.38 | | 0.35 | | 0.45 | | 0.35 | | 0.39 | |
| | | | | | | YM | | 0.22 | 0.38 | | | 0.40 | 0.58 | | | 0.27 | 0.43 | |
| | | | | | | XQS | 0.34 | | 0.39 | | 0.39 | | 0.50 | | 0.30 | | 0.42 | |
| | | | | | | YQS | | 0.44 | 0.54 | | | 0.58 | 0.70 | | | 0.32 | 0.50 | |
| | | | | | | TU | 0.28 | 0.30 | 0.45 | 0.07 | 0.33 | 0.48 | 0.64 | 0.05 | 0.28 | 0.28 | 0.42 | 0.08 |
| | | | | | | HGV | 0.26 | 0.22 | 0.43 | | 0.31 | 0.35 | 0.57 | | 0.25 | 0.23 | 0.47 | |
| T2 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 5.8 | XM | | | | | 0.40 | | 0.52 | | | | | |
| | | | | | | YM | | | | | | 0.39 | 0.57 | | | | | |
| | | | | | | XQS | | | | | 0.48 | | 0.58 | | | | | |
| | | | | | | YQS | | | | | | 0.62 | 0.78 | | | | | |
| | | | | | | TU | | | | | 0.27 | 0.44 | 0.63 | 0.15 | | | | |
| | | | | | | HGV | | | | | 0.79 | 0.30 | 1.01 | | | | | |
| T3 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 8.2 | XM | 0.48 | | 0.78 | | 0.41 | | 0.70 | | 0.43 | | 0.62 | |
| | | | | | | YM | | 0.46 | 0.66 | | | 0.57 | 0.80 | | | 0.34 | 0.61 | |
| | | | | | | XQS | 0.44 | | 0.62 | | 0.56 | | 0.87 | | 0.44 | | 0.60 | |
| | | | | | | YQS | | 0.73 | 0.85 | | | 0.48 | 0.81 | | | 0.28 | 0.65 | |
| | | | | | | TU | 0.37 | 0.45 | 0.69 | 0.08 | 0.46 | 0.51 | 0.71 | 0.09 | 0.37 | 0.25 | 0.52 | 0.07 |
| | | | | | | HGV | 0.43 | 0.30 | 0.60 | | 1.38 | 0.38 | 1.56 | | 0.38 | 0.30 | 0.60 | |
| T4 - BC5 | 0.33 | -0.20 | -1.7 | -4.2 | 3.4 | XM | 0.40 | | 0.47 | | 0.39 | | 0.50 | | 0.29 | | 0.43 | |
| | | | | | | YM | | 0.39 | 0.57 | | | 0.39 | 0.58 | | | 0.29 | 0.45 | |
| | | | | | | XQS | 0.53 | | 0.57 | | 0.45 | | 0.59 | | 0.37 | | 0.40 | |
| | | | | | | YQS | | 0.63 | 0.72 | | | 0.54 | 0.73 | | | 0.34 | 0.53 | |
| | | | | | | TU | 0.44 | 0.26 | 0.55 | 0.11 | 0.35 | 0.38 | 0.56 | 0.11 | 0.29 | 0.20 | 0.40 | 0.07 |
| | | | | | | HGV | 0.35 | 0.19 | 0.40 | | 0.44 | 0.39 | 0.65 | | 0.40 | 0.28 | 0.53 | |
| T5 - BC4 | 1.0 | -0.20 | -3.0 | -1.7 | 3.4 | XM | 0.88 | | 1.15 | | 0.85 | | 1.05 | | 0.97 | | 1.17 | |
| | | | | | | YM | | 0.79 | 1.32 | | | 0.50 | 1.01 | | | 0.56 | 1.14 | |
| | | | | | | XQS | 0.69 | | 1.03 | | 0.89 | | 1.07 | | 0.90 | | 1.07 | |
| | | | | | | YQS | | 0.87 | 1.58 | | | 0.49 | 1.03 | | | 0.48 | 1.15 | |
| | | | | | | TU | 0.73 | 0.65 | 1.02 | 0.10 | 0.71 | 0.73 | 1.12 | 0.13 | 0.76 | 0.48 | 0.94 | 0.05 |
| | | | | | | HGV | 0.83 | 0.44 | 1.16 | | 0.77 | 0.35 | 0.90 | | 0.83 | 0.42 | 1.15 | |

TABLE C-I (Concluded)

| Case - Basic Conf. | Stability ² Derivatives ² | | | | Turbu- lence, $\sigma_{u_g} = \sigma_{u_{g_0}}$ | Sub- task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|-----------------------------|--|-------|-------|--------------------|---|---------------------------|------------|-----------|---------|-----------|-----------|-----------|---------|-----------|-------------|-----------|---------|-----------|
| | M_{u_0} | X_u | M_q | $M_{\dot{\theta}}$ | | | Pilot A | | | | Pilot B | | | | Pilot C | | | |
| | | | | | | | M_{u_5} | L_{c_5} | Sim^4 | N_{c_5} | M_{c_5} | L_{c_5} | Sim^4 | N_{c_5} | M_{c_5} | L_{c_5} | Sim^4 | N_{c_5} |
| T6 - BC2 | 1.0 | -0.05 | -1.1 | -2.5 | 3.4 | XM | 1.09 | | 1.16 | | 0.89 | | 1.18 | | 1.07 | | 1.24 | |
| | | | | | | YM | | 0.75 | 1.37 | | | 0.64 | 1.25 | | | 0.74 | 1.36 | |
| | | | | | | XQS | 0.95 | | 1.18 | | 1.0 | | 1.28 | | 1.09 | | 1.29 | |
| | | | | | | YQS | | 1.14 | 1.47 | | | 0.68 | 1.22 | | | 0.74 | 1.22 | |
| | | | | | | TU | 0.73 | 0.74 | 1.20 | 0.12 | 0.91 | 0.94 | 1.40 | 0.11 | 1.28 | 0.79 | 1.75 | 0.05 |
| | | | | | | HOV | 0.87 | 0.54 | 1.29 | | 0.98 | 0.45 | 1.01 | | 0.98 | 0.43 | 1.18 | |
| T13 - BC6 | 1.0 | -0.20 | -1.1 | -2.5 | 3.4 | XM | 0.87 | | 1.05 | | 0.92 | | 1.30 | | 0.90 | | 1.07 | |
| | | | | | | YM | | 0.31 | 1.31 | | | 0.65 | 1.30 | | | 0.58 | 1.06 | |
| | | | | | | XQS | 0.93 | | 1.05 | | 0.99 | | 1.22 | | 0.87 | | 1.01 | |
| | | | | | | YQS | | 1.37 | 1.90 | | | 0.80 | 1.39 | | | 0.62 | 1.11 | |
| | | | | | | TU | 0.81 | 0.68 | 1.08 | 0.09 | 0.95 | 0.75 | 1.32 | 0.13 | 0.89 | 0.52 | 1.14 | 0.13 |
| | | | | | | HOV | 0.65 | 0.58 | 1.20 | | 0.77 | 0.37 | 0.98 | | 0.79 | 0.42 | 1.07 | |
| T14 - BC6 | 1.0 | -0.20 | -1.1 | -2.5 | 5.8 | XM | | | | | 1.13 | | 1.60 | | 1.09 | | 1.50 | |
| | | | | | | YM | | | | | | 0.92 | 1.64 | | | 0.83 | | |
| | | | | | | XQS | | | | | 1.31 | | | | 1.13 | | 1.30 | |
| | | | | | | YQS | | | | | | 0.86 | | | | 0.72 | 1.39 | |
| | | | | | | TU | | | | | 1.00 | 1.13 | 2.63 | 0.13 | 0.90 | 0.70 | 1.27 | 0.05 |
| | | | | | | HOV | | | | | 1.31 | 0.97 | | | 1.03 | 0.54 | 1.24 | |
| T15 - BC6 | 1.0 | -0.20 | -1.1 | -2.5 | 8.2 | XM | 1.17 | | 1.90 | | 1.08 | | 1.85 | | | | | |
| | | | | | | YM | | 1.21 | 1.87 | | | 0.93 | 1.58 | | | | | |
| | | | | | | XQS | 1.57 | | 2.20 | | 1.18 | | 1.70 | | | | | |
| | | | | | | YQS | | 1.51 | 2.00 | | | 1.29 | | | | | | |
| | | | | | | TU | 1.53 | 1.07 | 1.90 | 0.18 | 1.09 | 1.21 | | 0.12 | | | | |
| | | | | | | HOV | 1.21 | 1.14 | 1.90 | | 1.19 | 1.04 | 1.87 | | | | | |
| T16 - BC3 | 1.0 | -0.05 | -2.0 | 0 | 3.4 | XM | 0.97 | | 1.28 | | 0.98 | | 1.18 | | 1.14 | | 1.31 | |
| | | | | | | YM | | 0.82 | 1.35 | | | 0.97 | 1.41 | | | 0.55 | 1.33 | |
| | | | | | | XQS | 1.02 | | 1.24 | | 1.03 | | 1.21 | | 1.24 | | 1.50 | |
| | | | | | | YQS | | 1.32 | 1.80 | | | 0.80 | 1.24 | | | 0.54 | 1.16 | |
| | | | | | | TU | 0.91 | 0.80 | 1.35 | 0.11 | 1.35 | 0.83 | 1.60 | 0.13 | 0.98 | 0.65 | 1.16 | 0.01 |
| | | | | | | HOV | 0.81 | 0.60 | 1.24 | | 0.88 | 0.60 | 1.29 | | 0.87 | 0.35 | 1.04 | |

1. Wind simulation included mean wind, $U_m = 10$ kts. Thrust vector control available to trim longitudinal steady forces.
2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; TU, ± 180 deg turn-over-a-spot; HOV, precision hover.
4. Sim.: Simultaneous control moment usage, exceedance computations performed on the function $(|M_c| + |L_c|)$.

TABLE C-II (Concluded)

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Lag T_e, T_a | Delay d_e, d_a | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|-------|---------------|--------------------|-------------------|---------------------|---------------------------|------------|----------|-------------------|----------|----------|----------|-------------------|----------|-------------|----------|-------------------|----------|
| | | | | | | | | Pilot A | | | | Pilot B | | | | Pilot C | | | |
| | $M_{\dot{u}}$ | X_u | $M_{\dot{q}}$ | $M_{\dot{\theta}}$ | | | | M_{c5} | L_{c5} | Sim. ⁴ | N_{c5} | M_{c5} | L_{c5} | Sim. ⁴ | N_{c5} | M_{c5} | L_{c5} | Sim. ⁴ | N_{c5} |
| LL-5 - BC6 | 1.0 | -0.20 | -1.1 | -2.5 | 0.60 | 0 | XM | | | | | 0.81 | | 1.13 | | | | | |
| | | | | | | | YM | | | | | | 0.59 | 1.28 | | | | | |
| | | | | | | | XQS | | | | | 0.78 | | 1.04 | | | | | |
| | | | | | | | YQS | | | | | | 0.68 | 1.29 | | | | | |
| | | | | | | | TU | | | | | 0.96 | 0.72 | 1.37 | 0.08 | | | | |
| | | | | | | | HOV | | | | | 0.94 | 0.58 | 1.18 | | | | | |
| LL-23 - BC1 | 0.33 | -0.20 | -1.7 | -4.2 | 0 | 0.2 | XM | | | | | 0.34 | | 0.48 | | | | | |
| | | | | | | | YM | | | | | | 0.29 | 0.47 | | | | | |
| | | | | | | | XQS | | | | | 0.35 | | 0.42 | | | | | |
| | | | | | | | YQS | | | | | | 0.53 | 0.67 | | | | | |
| | | | | | | | TU | | | | | 0.29 | 0.34 | 0.52 | 0.12 | | | | |
| | | | | | | | HOV | | | | | 0.31 | 0.35 | 0.57 | | | | | |
| LL-24 - BC1 | 0.33 | -0.20 | -1.7 | -4.2 | 0.3 | 0.1 | XM | | | | | 0.33 | | 0.41 | | | | | |
| | | | | | | | YM | | | | | | 0.25 | 0.48 | | | | | |
| | | | | | | | XQS | | | | | 0.33 | | 0.39 | | | | | |
| | | | | | | | YQS | | | | | | 0.37 | 0.56 | | | | | |
| | | | | | | | TU | | | | | 0.25 | 0.24 | 0.39 | 0.11 | | | | |
| | | | | | | | HOV | | | | | 0.29 | 0.19 | 0.41 | | | | | |
| LL-25 - BC1 | 0.33 | -0.20 | -1.7 | -4.2 | 0.3, 0 | 0.1, 0 | XM | | | | | 0.59 | | 1.24 | | | | | |
| | | | | | | | YM | | | | | | 1.10 | 1.29 | | | | | |
| | | | | | | | XQS | | | | | 0.85 | | 1.33 | | | | | |
| | | | | | | | YQS | | | | | | 1.14 | 1.34 | | | | | |
| | | | | | | | TU | | | | | 0.68 | | | 0.09 | | | | |
| | | | | | | | HOV | | | | | 0.55 | 0.95 | 1.27 | | | | | |

1. Wind simulation included mean wind, $U_m = 10$ kts. Thrust vector control available to trim longitudinal steady forces.
2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; TU, ≈ 180 deg turn-over-a-spot; HOV, precision hover.
4. Sim.: Simultaneous control moment usage, exceedance computations performed on the function $(|M_c| + |L_c|)$.

TABLE C-III

PERCENT TIME PITCH, ROLL AND YAW CONTROL-MOMENT
COMMANDS EXCEEDED INSTALLED MOMENT LIMITS

Vertical and Directional Parameters Listed in Table A-I
See End of Table for Explanation of Notes

| Case ¹ Basic Conf. | Stability Derivatives ² | | | | Maximum Control Moment Available | | | Lag τ_c/τ_a | Delay d_e, d_a | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|-------------------------------------|---------------------------------------|-------|-------|-------|--|----------|----------|------------------------|---------------------|---------------------------|------------|----------|----------|----------|----------|----------|----------|----------|-------------|----------|----------|----------|
| | M_{uB} | X_u | M_q | M_g | M_{cw} | L_{cw} | N_{cw} | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | | | | | | | | | | | P_{RL} | P_{LL} | P_{SL} | P_{RH} | P_{RL} | P_{LL} | P_{SL} | P_{RH} | P_{RL} | P_{LL} | P_{SL} | P_{RH} |
| LM1 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 0.360 | 0.115 | 0.120 | 0 | 0 | XM | | | | | 7.6 | | 1.6 | | 14.9 | | 0 | |
| | | | | | | | | | | YM | | | | | | 4.4 | 0.4 | | | 0 | 0 | |
| | | | | | | | | | | XQS | | | | | 21.1 | | 13.0 | | 9.7 | | 0 | |
| | | | | | | | | | | YQS | | | | | | 8.6 | 4.0 | | | 0 | 0 | |
| | | | | | | | | | | TU | | | | | 1.2 | 2.3 | 0 | 3.1 | 2.0 | 1.3 | 0 | 2.8 |
| | | | | | | | | | | HOV | | | | | 3.0 | 1.1 | 0.2 | | 0.8 | 0.2 | 0 | |
| LM2 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 0.396 | 0.457 | 0.132 | 0 | 0 | XM | 0 | | 0 | | 0.9 | | 0 | | 0 | | 0 | |
| | | | | | | | | | | YM | | 0 | 0 | | | 0.5 | 0 | | | 0 | 0 | |
| | | | | | | | | | | XQS | 0 | | 0 | | 8.1 | | 0 | | 7.7 | | 0 | |
| | | | | | | | | | | YQS | | 0 | 0 | | | 4.3 | 0 | | | 0.2 | 0 | |
| | | | | | | | | | | TU | 0 | 0 | 0 | 0 | 0.9 | 1.5 | 0 | 0 | 0.3 | 0.4 | 0 | 0 |
| | | | | | | | | | | HOV | 0 | 0 | 0 | | 2.0 | 0.3 | 0 | | 0.2 | 0 | 0 | |
| LM3 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 0.432 | 0.493 | 0.144 | 0 | 0 | XM | | | | | 2.3 | | 0 | | | | | |
| | | | | | | | | | | YM | | | | | | 0.1 | 0 | | | | | |
| | | | | | | | | | | XQS | | | | | 2.0 | | 0 | | | | | |
| | | | | | | | | | | YQS | | | | | | 2.8 | 0 | | | | | |
| | | | | | | | | | | TU | | | | | 0 | 1.6 | 0 | 0 | | | | |
| | | | | | | | | | | HOV | | | | | 1.9 | 0.3 | 0 | | | | | |
| LM4 - BC5 | 0.33 | -0.20 | -1.7 | -4.2 | 0.300 | 0.280 | 0.120 | 0 | 0 | XM | | | | | | | | | 1.02 | | 0 | |
| | | | | | | | | | | YM | | | | | | | | | | 1.6 | 0 | |
| | | | | | | | | | | XQS | | | | | | | | | 0 | | 0 | |
| | | | | | | | | | | YQS | | | | | | | | | | 2.0 | 0 | |
| | | | | | | | | | | TU | | | | | | | | | 0.6 | 1.7 | 0 | 0 |
| | | | | | | | | | | HOV | | | | | | | | | 0 | 0.3 | 0 | |
| LM6 - BC5 | 0.23 | -0.20 | -1.7 | -4.2 | 0.350 | 0.369 | 0.150 | 0 | 0 | XM | 0 | | 0 | | | | | | | | | |
| | | | | | | | | | | YM | | 3.7 | 0 | | | | | | | | | |
| | | | | | | | | | | XQS | 3.5 | | 0 | | | | | | | | | |
| | | | | | | | | | | YQS | | 18.3 | 0 | | | | | | | | | |
| | | | | | | | | | | TU | 1.6 | 2.2 | 0 | 0 | | | | | | | | |
| | | | | | | | | | | HOV | 0 | 1.9 | 0 | | | | | | | | | |
| LM9 - BC4 | 1.0 | -0.20 | -3.0 | -1.7 | 0.902 | 0.666 | 0.193 | 0 | 0 | XM | | | | | 1.8 | | 0 | | | | | |
| | | | | | | | | | | YM | | | | | | 0 | 0 | | | | | |
| | | | | | | | | | | XQS | | | | | 2.4 | | 0 | | | | | |
| | | | | | | | | | | YQS | | | | | | 0.1 | 0 | | | | | |
| | | | | | | | | | | TU | | | | | | 0.5 | 6.1 | 0 | 0 | | | |
| | | | | | | | | | | HOV | | | | | | 0 | 0 | 0 | | | | |

TABLE C-III (Concluded)

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Maximum Control Moments Available | | | Lag $\tau_{\epsilon}, \tau_{\delta}$ | Delay $\epsilon_{\epsilon}, \epsilon_{\delta}$ | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|---------------|---------------|---------------|---|-------------------|-------------------|---|---|---------------------------|------------|----------|----------|----------|----------|----------|----------|----------|-------------|----------|----------|----------|
| | $M_{\dot{\delta}}$ | $X_{\dot{u}}$ | $Y_{\dot{q}}$ | $M_{\dot{g}}$ | $M_{C_{\dot{m}}}$ | $L_{C_{\dot{m}}}$ | $N_{C_{\dot{m}}}$ | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | | | | | | | | | | | P_{ML} | P_{LL} | P_{SL} | P_{NL} | P_{VL} | P_{LL} | P_{SL} | P_{NL} | P_{VI} | P_{LI} | P_{SI} | P_{NI} |
| LM10 - BC4 | 1.0 | -0.20 | -3.0 | -1.7 | 0.954 | 0.727 | 0.211 | 0 | 0 | XM | 0.3 | | 0 | | 2.3 | | 0 | | 0.2 | | 0.2 | |
| | | | | | | | | | | YM | | 0.1 | 0 | | | 0.3 | 0 | | | 0 | | |
| | | | | | | | | | | XQS | 1.7 | | 0 | | 0.8 | | 0 | | 3.2 | | 0.0 | |
| | | | | | | | | | | YQS | | 0 | 0 | | | 0 | 0 | | | 0.05 | 0.0 | |
| | | | | | | | | | | TU | 0 | 0 | 0 | 0 | 0 | 7.7 | 0 | 0 | 0.5 | 2.7 | 0 | 0 |
| | | | | | | | | | | HOV | 0 | 0 | 0 | | 1.6 | 0 | 0 | | 0.2 | 0 | 0 | |
| LM13 - BC5 | 1.0 | -0.2 | -1.1 | -2.5 | 0.979 | 0.825 | 0.187 | 0 | 0 | XM | 0 | | 0 | | 0.5 | | 0 | | | | | |
| | | | | | | | | | | YM | | 0 | 0 | | | 0.6 | 0 | | | | | |
| | | | | | | | | | | XQS | 0 | | 0 | | 6.2 | | 0 | | | | | |
| | | | | | | | | | | YQS | | 0.6 | 0 | | | 2.4 | 0 | | | | | |
| | | | | | | | | | | TU | | | | | 0.2 | 2.6 | 0 | 0 | | | | |
| | | | | | | | | | | HOV | | | | | 1.4 | 0.6 | 0 | | | | | |
| LM14 - BC5 | 1.0 | -0.2 | -1.1 | -2.5 | 1.068 | 0.900 | 0.204 | 0 | 0 | XM | | | | 0 | | 0 | | 0 | | 0 | | |
| | | | | | | | | | | YM | | | | | 0 | 0 | | | 0 | 0 | | |
| | | | | | | | | | | XQS | | | | | 0 | 0 | 0 | | | 0 | 0 | |
| | | | | | | | | | | TU | | | | | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |
| | | | | | | | | | | HOV | | | | | 0.2 | 0 | 0 | | 0 | 0 | 0 | |
| | | | | | | | | | | | | | | | | | | | | | | |
| LM15 - BC5 | 1.0 | -0.2 | -1.1 | -2.5 | 1.157 | 0.975 | 0.221 | 0 | 0 | XM | 0 | | 0 | | | | | | | | | |
| | | | | | | | | | | YM | | 0 | 0 | | | | | | | | | |
| | | | | | | | | | | XQS | 0 | | 0 | | | | | | | | | |
| | | | | | | | | | | YQS | | 3.0 | 0 | | | | | | | | | |
| | | | | | | | | | | TU | 0.1 | 0 | 0 | 0 | | | | | | | | |
| | | | | | | | | | | HOV | 0 | 0 | 0 | | | | | | | | | |
| LM17 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 0.396 | 0.457 | 0.132 | 0.3 | 0.1 | XM | | | | | 0.6 | | 0 | | 0.1 | | 0 | |
| | | | | | | | | | | YM | | | | | | 0 | 0 | | | 0 | 0 | |
| | | | | | | | | | | XQS | | | | | 1.5 | | 0 | | 2.1 | | 0 | |
| | | | | | | | | | | YQS | | | | | | 8.8 | 0 | | | 0 | 0 | |
| | | | | | | | | | | TU | | | | | 0.3 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | HOV | | | | | 1.2 | 1.1 | 0 | | 0.4 | 0.2 | 0 | |
| LM18 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 0.432 | 0.498 | 0.144 | 0.3 | 0.1 | XM | | | | | | | | 0 | | 0 | | |
| | | | | | | | | | | YM | | | | | | | | | | 0 | 0 | |
| | | | | | | | | | | YQS | | | | | | | | | 0.6 | | 0 | |
| | | | | | | | | | | XQS | | | | | | | | | | 0 | 0 | |
| | | | | | | | | | | TU | | | | | | | | | 0 | 0 | 0 | 0 |
| | | | | | | | | | | HOV | | | | | | | | | 0.1 | 0 | 0 | |

1. Wind simulation included mean wind, $U_m = 10$ kts. Thrust vector control available to trim longitudinal steady forces.

2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.

3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; TU, ± 180 deg turn-over-a-spot; HOV, precision hover.

4. P_{G_j} : Percent time that commanded moments exceeded installed limit on simultaneous control moment usage, ($M_{C_j} + L_{C_j}$).

TABLE C-IV

PITCH, ROLL AND YAW CONTROL-MOMENT LEVELS EXCEEDED 5 PERCENT
OF THE TIME FROM THE STUDY OF INTER-AXIS MOTION COUPLING

Vertical and Directional Parameters Listed in Table A-I

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Motion Coupling Parameters | | | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|----------------|----------------|----------------|----------------------------------|----------------|--------------------------------|--------------------------------|---------------------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|------------------|-----------------|
| | | | | | | | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | M _{uS} | X _u | M _q | M _g | M _p | Y _q | M _u /L _u | L _q /M _q | | N _{cs} | L _{cs} | Sim ⁴ | N _{cs} | N _{cs} | L _{cs} | Sim ⁴ | N _{cs} | N _{cs} | L _{cs} | Sim ⁴ | N _{cs} |
| LC1 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 2 | -2 | 0 | 0 | XM | | | | | 0.48 | | 0.67 | | 0.36 | | 0.43 | |
| | | | | | | | | | YM | | | | | | 0.39 | 0.66 | | | 0.24 | 0.49 | |
| | | | | | | | | | XQS | | | | | 0.43 | | 0.64 | | 0.48 | | 0.59 | |
| | | | | | | | | | YQS | | | | | | 0.56 | 1.05 | | | 0.35 | 0.76 | |
| | | | | | | | | | TU | | | | | 0.41 | 0.36 | 0.66 | 0.17 | 0.29 | 0.30 | 0.44 | |
| | | | | | | | | | HOV | | | | | 0.54 | 0.41 | 0.86 | | 0.37 | 0.19 | 0.47 | |
| LC2 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 4 | -4 | 0 | 0 | XM | | | | | 0.61 | | 0.88 | | | | | |
| | | | | | | | | | YM | | | | | | 0.54 | 0.96 | | | | | |
| | | | | | | | | | XQS | | | | | 0.81 | | 1.24 | | | | | |
| | | | | | | | | | YQS | | | | | | 0.91 | 1.57 | | | | | |
| | | | | | | | | | TU | | | | | 0.57 | 0.47 | 0.87 | 0.16 | | | | |
| | | | | | | | | | HOV | | | | | 0.68 | 0.47 | 1.01 | | | | | |
| LC4 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 0 | 0 | 0.50 | -0.50 | XM | 0.40 | | 0.58 | | 0.39 | | 0.64 | | 0.34 | | 0.42 | |
| | | | | | | | | | YM | | 0.40 | 0.56 | | | 0.38 | 0.64 | | | 0.24 | 0.45 | |
| | | | | | | | | | XQS | 0.58 | | 0.79 | | 0.47 | | 0.68 | | 0.36 | | 0.42 | |
| | | | | | | | | | YQS | | 0.70 | 1.00 | | | 0.65 | | | | 0.31 | 0.54 | |
| | | | | | | | | | TU | 0.36 | 0.40 | 0.58 | 0.11 | 0.28 | 0.30 | 0.47 | 0.23 | 0.27 | 0.24 | 0.38 | |
| | | | | | | | | | HOV | 0.37 | 0.29 | 0.51 | | 0.37 | 0.34 | 0.65 | | 0.29 | 0.18 | 0.38 | |
| LC5 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 2 | -2 | 0.25 | -0.25 | XM | 0.37 | | 0.47 | | 0.43 | | 0.57 | | 0.35 | | 0.48 | |
| | | | | | | | | | YM | | 0.37 | 0.66 | | | 0.39 | 0.69 | | | 0.33 | 0.53 | |
| | | | | | | | | | XQS | 0.53 | | 0.70 | | 0.49 | | 0.72 | | 0.47 | | 0.62 | |
| | | | | | | | | | YQS | | 0.72 | 1.23 | | | 0.63 | 1.10 | | | 0.33 | 0.61 | |
| | | | | | | | | | TU | 0.32 | 0.33 | 0.53 | 0.06 | 0.40 | 0.39 | 0.65 | 0.17 | 0.29 | 0.24 | 0.41 | 0.05 |
| | | | | | | | | | HOV | 0.39 | 0.29 | 0.54 | | 0.53 | 0.39 | 0.78 | | 0.35 | 0.19 | 0.46 | |
| LC8 - BC2 | 0.0 | -0.05 | -2.5 | -0.5 | 2 | -2 | -0.25 | 0.25 | XM | | | | | 0.87 | | 1.06 | | | | | |
| | | | | | | | | | YM | | | | | | 0.71 | 1.28 | | | | | |
| | | | | | | | | | XQS | | | | | 0.85 | | 1.09 | | | | | |
| | | | | | | | | | YQS | | | | | | 0.70 | 1.32 | | | | | |
| | | | | | | | | | TU | | | | | 0.90 | 0.68 | 1.34 | 0.17 | | | | |
| | | | | | | | | | HOV | | | | | 0.77 | 0.47 | 1.03 | | | | | |

1. Wind simulation included mean wind, $U_m = 10$ kts. Thrust vector control available to trim longitudinal steady forces.
2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; TU, ± 180 deg turn-over-a-spot; HOV, precision hover.
4. Sim.: Simultaneous control moment usage, exceedance computations performed on the function $(|M_c| + |L_c|)$.

TABLE C-V

PITCH CONTROL-MOMENT AND THRUST-VECTOR-ANGLE LEVELS EXCEEDED 5 PERCENT
OF THE TIME FROM THE STUDY OF INDEPENDENT THRUST-VECTOR CONTROL

Vertical and Directional Parameters Listed in Table A-I

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Thrust- Vector Control Param. | | | Sub- Task ³ | Fixed Base | | | | Moving Base | |
|--|---------------------------------------|-------|-------|--------------------|--|--------------------|------------------|---------------------------|------------|------|-----------|------|-------------|------|
| | | | | | | | | | Pilot A | | Pilot B | | Pilot B | |
| | $M_{\dot{\theta}S}$ | X_u | M_q | $M_{\dot{\theta}}$ | $\dot{\gamma}^4$ | $\dot{\gamma}_0^5$ | \dot{M}_{TS}^5 | | M_{c_s} | TV | M_{c_s} | TV | M_{c_s} | TV |
| LI1 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 5 | - | - | XM | 0.33 | | 0.29 | | 0.25 | |
| | | | | | | | | XQS | 0.29 | | 0.34 | | 0.33 | |
| | | | | | | | | TU | 0.27 | 2.77 | 0.31 | 7.86 | 0.21 | 2.00 |
| | | | | | | | | HOV | 0.29 | | 0.30 | | 0.25 | |
| LI3 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | 20 | - | - | XM | | | 0.32 | | 0.28 | |
| | | | | | | | | XQS | | | 0.33 | | 0.27 | |
| | | | | | | | | TU | | | 0.22 | 5.50 | 0.24 | 2.50 |
| | | | | | | | | HOV | | | 0.29 | | 0.27 | |
| LI6 - BC4 | 1.0 | -0.20 | -3 | -1.7 | 20 | - | - | XM | 0.93 | | 0.93 | | 0.80 | |
| | | | | | | | | XQS | 0.88 | | 0.89 | | 0.86 | |
| | | | | | | | | TU | 0.79 | 9.15 | 0.81 | 10.6 | 0.67 | 4.20 |
| | | | | | | | | HOV | 0.72 | | 0.75 | | 0.68 | |
| LI12 - BC1 | 0.33 | -0.05 | -1.7 | -4.2 | - | 5 | 1 | XM | | | 0.35 | | | |
| | | | | | | | | XQS | | | 0.39 | | | |
| | | | | | | | | TU | | | 0.29 | 20.6 | | |
| | | | | | | | | HOV | | | 0.32 | | | |

1. Standard wind simulation; $\sigma_{\dot{\theta}S} = \sigma_{\dot{\gamma}S} = 3.4$ ft/sec, $U_m = 10$ kts.
2. Symmetrical Configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Key: XM, longitudinal maneuvering; XQS, longitudinal quick stop; TU, ± 180 deg turn-over-a-spot; HOV, precision hover.
4. Thumb switch thrust vector angle control, conventional attitude control.
5. Control stick thrust vector control, thumb switch attitude control.

TABLE C-VI

PITCH, ROLL AND YAW CONTROL-MOMENT LEVELS EXCEEDED 5 PERCENT OF
THE TIME FROM THE STUDY OF RATE-COMMAND/ATTITUDE-HOLD CONTROL

Vertical and Directional Parameters Listed in Table A-I

See End of Table for Explanation of Notes

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Params. for Second- Order Dynamics | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|----------------|----------------|----------------|--|----------------|---------------------------|-----------------|-----------------|-------------------|-----------------|-----------------|-----------------|-------------------|-----------------|-----------------|-----------------|-------------------|-----------------|
| | | | | | | | | Pilot A | | | | Pilot B | | | | Pilot F | | | |
| | M _u S | X _u | M _q | N _q | S | ω _n | | M _{c5} | L _{c5} | Sim. ⁴ | N _{c5} | M _{c5} | L _{c5} | Sim. ⁴ | N _{c5} | M _{c5} | L _{c5} | Sim. ⁴ | N _{c5} |
| LR1 - BC1 | 0.33 | -0.05 | -2 | -8 | 0.39 | 2.8 | XM | | | | | 0.58 | | 0.65 | | | | | |
| | | | | | | | YM | | | | | | 0.58 | 0.90 | | | | | |
| | | | | | | | XQS | | | | | 0.89 | | 0.98 | | | | | |
| | | | | | | | YQS | | | | | | 0.75 | 1.01 | | | | | |
| | | | | | | | TU | | | | | 0.54 | 0.45 | 0.75 | 0.11 | | | | |
| | | | | | | | HCV | | | | | 0.62 | 0.50 | 0.86 | | | | | |
| LR2 - BC1 | 0.33 | -0.05 | -2 | -10 | 0.16 | 6.3 | XM | | | | | 0.66 | | 0.84 | | 0.30 | | 0.30 | |
| | | | | | | | YM | | | | | | 0.58 | 0.93 | | | 0.27 | 0.46 | |
| | | | | | | | XQS | | | | | 0.97 | | 1.08 | | 0.34 | | 0.38 | |
| | | | | | | | YQS | | | | | | 0.74 | 1.17 | | | 0.28 | 0.45 | |
| | | | | | | | TU | | | | | 0.57 | 0.47 | 0.85 | 0.37 | 0.24 | 0.34 | 0.44 | |
| | | | | | | | HCV | | | | | 0.69 | 0.48 | 1.07 | | 0.77 | 0.21 | 0.40 | |
| LR3 - BC1 | 0.33 | -0.05 | -4 | -8 | 0.72 | 2.8 | XM | | | | | 0.45 | | 0.59 | | | | | |
| | | | | | | | YM | | | | | | 0.42 | 0.72 | | | | | |
| | | | | | | | XQS | | | | | 0.59 | | 0.82 | | | | | |
| | | | | | | | YQS | | | | | | 0.66 | 1.00 | | | | | |
| | | | | | | | TU | | | | | 0.37 | 0.39 | 0.63 | 0.13 | | | | |
| | | | | | | | HCV | | | | | 0.41 | 0.44 | 0.73 | | | | | |

TABLE C-VI (Continued)

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Param. for Second- Order Dynamics | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|----------------|----------------|--------------------|---|------------|---------------------------|-------------|-------------|---------|-------------|-------------|-------------|---------|-------------|-------------|-------------|---------|-------------|
| | | | | | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | $N_{u\dot{u}}$ | $X_{u\dot{u}}$ | $Y_{u\dot{u}}$ | $N_{\dot{\theta}}$ | ζ | ω_n | | M_{ζ} | L_{ζ} | Sim^4 | N_{ζ} | M_{ζ} | L_{ζ} | Sim^4 | N_{ζ} | M_{ζ} | L_{ζ} | Sim^4 | N_{ζ} |
| LR5 - EC1 | 0.33 | -0.05 | -6 | -12 | 0.87 | 3.44 | XM | | | | | 0.44 | | 0.58 | | | | | |
| | | | | | | | YM | | | | | | 0.42 | 0.60 | | | | | |
| | | | | | | | XQS | | | | | 0.45 | | 1.00 | | | | | |
| | | | | | | | YQS | | | | | | 0.81 | 1.02 | | | | | |
| | | | | | | | TU | | | | | 0.35 | 0.42 | 0.55 | 0.12 | | | | |
| | | | | | | | HOV | | | | | 0.43 | 0.41 | 0.62 | | | | | |
| LR6 - EC1 | 0.33 | -0.05 | -6 | -40 | 0.47 | 6.32 | XM | | | | | 0.48 | | 0.62 | | 0.24 | | 0.37 | |
| | | | | | | | YM | | | | | | 0.44 | 0.69 | | | 0.28 | 0.47 | |
| | | | | | | | XQS | | | | | 0.50 | | 0.65 | | 0.24 | | 0.38 | |
| | | | | | | | YQS | | | | | | 0.56 | 0.77 | | | 0.26 | 0.44 | |
| | | | | | | | TU | | | | | 0.34 | 0.35 | 0.51 | 0.13 | 0.27 | 0.24 | 0.39 | |
| | | | | | | | HOV | | | | | 0.40 | 0.38 | 0.65 | | 0.29 | 0.20 | 0.40 | |
| LR8 - EC1 | 0.33 | -0.05 | -10 | -20 | | | XM | 0.29 | | 0.35 | | | | | | | | | |
| | | | | | | | YM | | 0.20 | 0.40 | | | | | | | | | |
| | | | | | | | XQS | | | 0.44 | | | | | | | | | |
| | | | | | | | YQS | | 0.47 | 0.55 | | | | | | | | | |
| | | | | | | | TU | 0.20 | 0.28 | 0.39 | 0.09 | | | | | | | | |
| | | | | | | | HOV | 0.23 | 0.19 | 0.37 | | | | | | | | | |

TABLE C-VI (Concluded)

| Case ¹ - Basic Conf. | Stability Derivatives ² | | | | Params. for Second- Order Dynamics | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|--|---------------------------------------|-------|-------|--------------------|--|------------|---------------------------|------------|----------|------------------|----------|----------|----------|------------------|----------|-------------|----------|------------------|----------|
| | | | | | | | | Pilot A | | | | Pilot B | | | | Pilot C | | | |
| | M_{uS} | X_u | M_q | $M_{\dot{\theta}}$ | ζ | ω_n | | N_{c5} | L_{c5} | Sim ⁴ | N_{c5} | N_{c7} | L_{c5} | Sim ⁴ | N_{c5} | N_{c5} | N_{c5} | Sim ⁴ | N_{c5} |
| LR10 - BC ⁴ | 1.0 | -0.20 | -2 | -25 | 0.20 | 5 | XM | | | | | 1.40 | | 1.93 | | | | | |
| | | | | | | | YM | | | | | | 1.06 | 1.60 | | | | | |
| | | | | | | | XQS | | | | | 1.37 | | 1.90 | | | | | |
| | | | | | | | YQS | | | | | | 1.03 | 1.67 | | | | | |
| | | | | | | | TU | | | | | 1.03 | 1.01 | 1.61 | 0.18 | | | | |
| | | | | | | | HOV | | | | | 1.19 | 0.83 | 1.75 | | | | | |
| LR11 - BC ⁴ | 1.0 | -0.20 | -4 | -16 | 0.50 | 4 | XM | | | | | 1.13 | | 1.50 | | 0.83 | | 1.09 | |
| | | | | | | | YM | | | | | | 0.90 | 1.63 | | | 0.53 | 1.13 | |
| | | | | | | | XQS | | | | | 1.15 | | 1.49 | | 0.83 | | 1.02 | |
| | | | | | | | YQS | | | | | | 0.99 | 1.75 | | | 0.48 | 1.08 | |
| | | | | | | | TU | | | | | 0.86 | 0.79 | 1.27 | 0.19 | 0.62 | 0.64 | 1.09 | |
| | | | | | | | HOV | | | | | 1.16 | 0.64 | 1.65 | | 0.60 | 0.29 | 0.86 | |
| LR14 - BC ⁴ | 1.0 | -0.20 | -6 | -26 | 0.61 | 5 | XM | | | | | 1.24 | | 1.93 | | 0.80 | | 0.99 | |
| | | | | | | | YM | | | | | | 0.92 | 1.76 | | | 0.57 | 1.07 | |
| | | | | | | | XQS | | | | | 1.05 | | 1.28 | | 0.75 | | 0.90 | |
| | | | | | | | YQS | | | | | | 0.71 | 1.22 | | | 0.59 | 1.13 | |
| | | | | | | | TU | | | | | 0.84 | 0.82 | 1.37 | 0.18 | 0.69 | 0.66 | 1.02 | |
| | | | | | | | HOV | | | | | 1.01 | 0.69 | 1.59 | | 0.67 | 0.30 | 0.85 | |

1. Wind simulation included mean wind, $U_m = 10$ kts. Thrust vector control available to trim longitudinal steady forces.
2. Symmetrical configuration - lateral derivative has same value as corresponding longitudinal derivative.
3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; TU, * 180 deg turn-over-a-spot; HOV, precision hover.
4. Sim: Simultaneous control moment usage, exceedance computations performed on the function $(|M_c| + |I_c|)$.

TABLE C-VII

PILOT COMMANDED AND TOTAL THRUST USAGE RESULTS FROM HEIGHT CONTROL STUDY

Longitudinal, Lateral and Directional Parameters Listed in Table A-I
See End of Table for Explanation of Notes

(a) Five-Percent Exceedance Levels for Pitching Moment, M_{c5} , and Incremental Thrust Increase Levels, $(T/W-1)_5$

| Case ¹ - Basic Conf. | Parameters ² | | | Lag, T_h | Delay, d_h | Sub- task ³ | Fixed Base | | | | | |
|--|-------------------------|-----------|-------|---------------|-----------------|---------------------------|------------|---|-------------------------------|----------|---|-------------------------------|
| | | | | | | | Pilot A | | | Pilot B | | |
| | Z_{w_s} | Z_{w_s} | T/W | | | | M_{c5} | $(T/W-1)_5$ for: | | M_{c5} | $(T/W-1)_5$ for: | |
| | | | | | | | | $Z_{\delta_c} \cdot \delta_c + Z_{w_s} \cdot w$ | $Z_{\delta_c} \cdot \delta_c$ | | $Z_{\delta_c} \cdot \delta_c + Z_{w_s} \cdot w$ | $Z_{\delta_c} \cdot \delta_c$ |
| H220 - BC1 | -0.125 | -0.125 | 1.13 | 0 | 0 | XM | 0.36 | 0.007 | 0.010 | 0.34 | 0.023 | 0.022 |
| | | | | | | YM | | 0.017 | 0.024 | | 0.025 | 0.024 |
| | | | | | | XQS | 0.36 | 0.009 | 0.020 | 0.37 | 0.019 | 0.024 |
| | | | | | | YQS | | 0.034 | 0.035 | | 0.034 | 0.034 |
| | | | | | | HQV | 0.30 | 0.010 | 0.016 | 0.36 | 0.017 | 0.023 |
| | | | | | | LS | 0.29 | 0.052 | 0.062 | 0.35 | 0.024 | 0.033 |
| H221 - BC1 | 0 | -0.25 | 1.10 | 0 | 0 | XM | 0.34 | 0.031 | 0.023 | 0.39 | 0.057 | 0.057 |
| | | | | | | YM | | 0.055 | 0.057 | | 0.048 | 0.045 |
| | | | | | | XQS | 0.47 | 0.030 | 0.029 | 0.37 | 0.026 | 0.029 |
| | | | | | | YQS | | 0.069 | 0.043 | | 0.047 | 0.034 |
| | | | | | | HQV | 0.29 | 0.029 | 0.038 | 0.33 | 0.014 | 0.023 |
| | | | | | | LS | 0.69 | 0.067 | | 0.32 | 0.061 | 0.067 |
| H222 - BC1 | -0.25 | 0 | 1.10 | 0 | 0 | XM | 0.36 | 0.024 | 0.018 | | | |
| | | | | | | YM | | 0.057 | 0.054 | | | |
| | | | | | | XQS | 0.47 | 0.047 | 0.047 | | | |
| | | | | | | YQS | | 0.050 | 0.048 | | | |
| | | | | | | HQV | 0.30 | 0.022 | 0.021 | | | |
| | | | | | | LS | 0.30 | 0.070 | 0.060 | | | |
| H223 - BC1 | -0.25 | -0.25 | 1.10 | 0 | 0 | XM | 0.37 | 0.008 | 0.005 | | | |
| | | | | | | YM | | 0.015 | 0.007 | | | |
| | | | | | | XQS | 0.46 | 0.007 | 0.008 | | | |
| | | | | | | YQS | | 0.026 | 0.018 | | | |
| | | | | | | HQV | 0.30 | 0.009 | 0.009 | | | |
| | | | | | | LS | 0.30 | 0.030 | 0.052 | | | |
| H21 - BC1 | 0 | 0 | 1.15 | 0 | 0 | XM | 0.39 | 0.042 | 0.042 | | | |
| | | | | | | YM | | 0.123 | 0.116 | | | |
| | | | | | | XQS | 0.32 | 0.082 | 0.095 | | | |
| | | | | | | YQS | | 0.108 | 0.108 | | | |
| | | | | | | HQV | 0.26 | 0.086 | 0.080 | | | |
| | | | | | | LS | 0.34 | 0.122 | 0.121 | | | |
| H24 - BC1 | -0.25 | -0.25 | 1.15 | 0 | 0 | XM | 0.24 | 0.009 | 0.017 | | | |
| | | | | | | YM | | 0.035 | 0.010 | | | |
| | | | | | | XQS | 0.39 | 0.006 | 0.010 | | | |
| | | | | | | YQS | | 0.054 | 0.015 | | | |
| | | | | | | HQV | 0.29 | 0.008 | 0.008 | | | |
| | | | | | | LS | 0.26 | 0.028 | 0.045 | | | |

TABLE C-VII (Continued)

| Case ¹ Basic Conf. | Parameters ² | | | Lag, τ_h | Delay, d_h | Sub- task ³ | Fixed Base | | | | | |
|-------------------------------------|-------------------------|-----------|--------|------------------|-----------------|---------------------------|---------------------------|---|-------------------------------|---------------------------|---|-------------------------------|
| | | | | | | | Pilot A | | | Pilot B | | |
| | | | | | | | (T/W-1) ₅ for: | | | (T/W-1) ₅ for: | | |
| | Z_{w_3} | Z_{w_5} | T/W | | | | M_{c5} | $Z_{\delta_c} \cdot \delta_c + Z_{w_5} \cdot w$ | $Z_{\delta_5} \cdot \delta_c$ | M_{c5} | $Z_{\delta_c} \cdot \delta_c + Z_{w_5} \cdot w$ | $Z_{\delta_c} \cdot \delta_c$ |
| HZ25 BC4 | 0 | 0 | > 1.15 | 0 | 0 | XM | | | | 1.027 | 0.089 | 0.091 |
| | | | | | | YM | | | | | 1.139 | 0.133 |
| | | | | | | XQS | | | | 0.68 | 0.157 | 0.167 |
| | | | | | | YQS | | | | | 0.132 | 0.133 |
| | | | | | | HOV | | | | 0.78 | 0.098 | 0.098 |
| | | | | | | LS | | | | 0.83 | 0.160 | 0.159 |
| HZ26 BC4 | -0.125 | -0.125 | 1.15 | 0 | 0 | XM | 0.89 | 0.025 | 0.028 | 0.85 | 0.029 | 0.045 |
| | | | | | | YM | | 0.028 | 0.019 | | 0.023 | 0.017 |
| | | | | | | XQS | 0.98 | 0.015 | 0.015 | 0.89 | 0.010 | 0.009 |
| | | | | | | YQS | | 0.043 | 0.039 | | 0.024 | 0.024 |
| | | | | | | HOV | 0.74 | 0.034 | 0.030 | 0.87 | 0.027 | 0.023 |
| | | | | | | LS | 0.84 | 0.070 | 0.069 | 0.87 | 0.034 | 0.042 |
| HZ27 BC4 | -0.25 | -0.25 | > 1.15 | 0 | 0 | XM | 0.85 | | 0.025 | | | |
| | | | | | | YM | | 0.017 | 0.039 | | | |
| | | | | | | XQS | 0.84 | 0.009 | 0.034 | | | |
| | | | | | | YQS | | 0.016 | 0.038 | | | |
| | | | | | | HOV | 0.72 | 0.008 | 0.035 | | | |
| | | | | | | LS | 0.76 | 0.016 | 0.079 | | | |
| HZ2 BC1 | -0.125 | -0.125 | 1.10 | 0.3 | 0 | XM | | | | 0.30 | 0.038 | 0.045 |
| | | | | | | YM | | | | | | |
| | | | | | | XQS | | | | 0.37 | 0.035 | 0.038 |
| | | | | | | YQS | | | | | 0.028 | 0.029 |
| | | | | | | HOV | | | | 0.30 | 0.023 | 0.027 |
| | | | | | | LS | | | | 0.29 | 0.048 | 0.053 |

TABLE C-VII (Concluded)

(b) Five-Percent Exceedance Levels for Pitching Moment, M_{c5} , and Percent Time Commanded T/W of Pilot and SAS Exceeds Installed T/W

| Case ¹ Basic Conf. | Parameters ² | | | Lag, τ_h | Delay, d_h | Sub- task ³ | Fixed Base | | | | | |
|-------------------------------------|-------------------------|-----------|------|------------------|-----------------|---------------------------|------------|---|---|----------|---|---|
| | | | | | | | Pilot A | | | Pilot B | | |
| | Z_{w_a} | Z_{w_s} | T/W | | | | M_{c5} | P_{TL} for $Z_{\delta_c} \cdot \delta_c + Z_{w_s} \cdot w$ | P_{TL} for $Z_{\delta_c} \cdot \delta_c$ | M_{c5} | P_{TL} for $Z_{\delta_c} \cdot \delta_c + Z_{w_s} \cdot w$ | P_{TL} for $Z_{\delta_c} \cdot \delta_c$ |
| H26 BC1 | -0.125 | -0.125 | 1.02 | 0 | 0 | XM | 0.36 | 19.0 | 27.0 | | | |
| | | | | | | YM | | 38.0 | 65.0 | | | |
| | | | | | | XQS | 0.14 | 21.0 | 30.0 | | | |
| | | | | | | YQS | | 14.0 | 60.0 | | | |
| | | | | | | HOV | 0.32 | 10.0 | 14.0 | | | |
| | | | | | | LS | 0.34 | 32.0 | 60.0 | | | |
| H210 BC1 | -0.25 | -0.25 | 1.02 | 0 | 0 | XM | 0.33 | 0.0 | 0.0 | | | |
| | | | | | | YM | | 3.0 | 0.0 | | | |
| | | | | | | XQS | 0.39 | 0.0 | 2.0 | | | |
| | | | | | | YQS | | 25.0 | 29.0 | | | |
| | | | | | | HOV | 0.29 | 2.0 | 1.0 | | | |
| | | | | | | LS | 0.28 | 17.0 | 16.0 | | | |
| H217 BC1 | -0.25 | -0.25 | 1.05 | 0 | 0 | XM | | | | 0.34 | 0.0 | 0.0 |
| | | | | | | YM | | | | | 0.0 | 0.0 |
| | | | | | | XQS | | | | 0.39 | 0.0 | 0.0 |
| | | | | | | YQS | | | | | 0.0 | 0.0 |
| | | | | | | HOV | | | | 0.36 | 0.0 | 0.0 |
| | | | | | | LS | | | | 0.32 | 3.0 | 8.0 |
| H12 BC1 | -0.125 | -0.125 | 1.05 | 0.3 | 0 | XM | 0.39 | 16.0 | 16.0 | | | |
| | | | | | | YM | | 0.0 | 0.0 | | | |
| | | | | | | XQS | 0.43 | 0.0 | 0.0 | | | |
| | | | | | | YQS | | 7.0 | 0.0 | | | |
| | | | | | | HOV | 0.34 | 0.0 | 0.0 | | | |
| | | | | | | LS | 0.34 | 2.0 | 4.0 | | | |

1. Wind simulation included mean wind, $U_{11} = 10$ kts. Thrust vector control available to trim longitudinal steady forces.

2. Symmetrical Configurations - lateral derivative has same value as corresponding longitudinal derivative.

3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; LS, landing sequence; HOV, precision hover.

TABLE C-VIII

YAW, PITCH AND ROLL CONTROL-MOMENT RESULTS
FROM THE DIRECTIONAL CONTROL STUDY

Longitudinal, Lateral and Vertical Parameters Listed in Table A-I
See End of Table for Explanation of Notes

(a) Five-Percent Exceedance Control-Moment Levels

| Case ¹ - Basic ² Conf. | N _V | Directional Parameters Varied | | | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|---|----------------|-------------------------------------|----------------------------|----------------|----------------|---------------------------|----------------------------|----------------------------|------------------|----------------------------|----------------------------|----------------------------|------------------|----------------------------|----------------------------|----------------------------|------------------|----------------------------|
| | | | | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | | R _r | N _{C₅} | T _ψ | d _ψ | | M _{C₅} | L _{C₅} | Sim ⁴ | N _{C₅} | M _{C₅} | L _{C₅} | Sim ⁴ | N _{C₅} | M _{C₅} | L _{C₅} | Sim ⁴ | N _{C₅} |
| D1 - BC1 | 0.005 | 0 | UL | 0 | 0 | XM | | | | | | | | | 0.40 | | 0.50 | |
| | | | | | | YM | | | | | | | | | | 0.26 | 0.43 | |
| | | | | | | XQS | | | | | | | | | 0.43 | | 0.51 | |
| | | | | | | YQS | | | | | | | | | | 0.27 | 0.49 | |
| | | | | | | TU | | | | | | | | | 0.30 | 0.28 | 0.46 | 0.14 |
| | | | | | | HOV | | | | | | | | | 0.35 | 0.18 | 0.40 | |
| D2 - BC1 | 0.005 | -0.5 | UL | 0 | 0 | XM | 0.39 | | 0.52 | | 0.42 | | 0.57 | | 0.38 | | 0.47 | |
| | | | | | | YM | | 0.29 | 0.56 | | | 0.38 | 0.58 | | | 0.26 | 0.48 | |
| | | | | | | XQS | 0.46 | | 0.55 | | 0.48 | | 0.59 | | 0.38 | | 0.46 | |
| | | | | | | YQS | | 0.46 | 0.67 | | | 0.37 | 0.61 | | | 0.30 | 0.56 | |
| | | | | | | TU | 0.29 | 0.29 | 0.46 | 0.13 | 0.31 | 0.33 | 0.45 | 0.14 | 0.28 | 0.22 | 0.39 | 0.14 |
| | | | | | | HOV | 0.35 | 0.22 | 0.45 | | 0.38 | 0.38 | 0.64 | | 0.37 | 0.23 | 0.50 | |
| D7 - BC1 | 0.005 | -0.5 | UL | 0.3 | 0 | XM | 0.33 | | 0.41 | | 0.40 | | 0.56 | | 0.46 | | 0.59 | |
| | | | | | | YM | | 0.29 | 0.44 | | | 0.44 | 0.68 | | | 0.34 | 0.62 | |
| | | | | | | XQS | 0.30 | | 0.41 | | 0.40 | | 0.50 | | 0.46 | | 0.58 | |
| | | | | | | YQS | | 0.38 | 0.57 | | | 0.44 | 0.62 | | | 0.32 | 0.63 | |
| | | | | | | TU | 0.29 | 0.29 | 0.43 | 0.15 | 0.33 | 0.37 | 0.59 | 0.12 | 0.35 | 0.27 | 0.49 | 0.17 |
| | | | | | | HOV | 0.29 | 0.18 | 0.39 | | 0.38 | 0.33 | 0.58 | | 0.40 | 0.25 | 0.62 | |
| D8 - BC1 | 0.005 | -0.5 | UL | 0.3 | 0.1 | XM | | | | | | | | | 0.42 | | 0.63 | |
| | | | | | | YM | | | | | | | | | | 0.31 | 0.64 | |
| | | | | | | XQS | | | | | | | | | 0.40 | | 0.53 | |
| | | | | | | YQS | | | | | | | | | | 0.29 | 0.59 | |
| | | | | | | TU | | | | | | | | | 0.30 | 0.24 | 0.45 | 0.16 |
| | | | | | | HOV | | | | | | | | | 0.39 | 0.24 | 0.56 | |
| D13 - BC1 | 0.005 | -1 | UL | 0.3 | 0 | XM | | | | | | | | | 0.43 | | 0.55 | |
| | | | | | | YM | | | | | | | | | | 0.28 | 0.59 | |
| | | | | | | XQS | | | | | | | | | 0.39 | | 0.53 | |
| | | | | | | YQS | | | | | | | | | | 0.29 | 0.56 | |
| | | | | | | TU | | | | | | | | | 0.35 | 0.26 | 0.40 | 0.16 |
| | | | | | | HOV | | | | | | | | | 0.39 | 0.27 | 0.55 | |

TABLE C-VIII (Concluded)

(a) Five-Percent Exceedance Control-Moment Levels

| Case ¹ - Basic ² Conf. | N_V | Directional Parameters Varied | | | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|---|-------|-------------------------------------|----------|-------|--------------|---------------------------|------------|----------|-------------------|----------|----------|----------|-------------------|----------|-------------|----------|-------------------|----------|
| | | | | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | | N_T | N_{cm} | T_y | $\delta\psi$ | | M_{c5} | L_{c5} | Sim. ⁴ | N_{c5} | M_{c5} | L_{c5} | Sim. ⁴ | N_{c5} | M_{c5} | L_{c5} | Sim. ⁴ | N_{c5} |
| D14 - BC1 | 0.005 | -1 | UL | 0.6 | 0 | XM | | | | | | | | | 0.42 | | 0.56 | |
| | | | | | | YM | | | | | | | | | | 0.28 | 0.52 | |
| | | | | | | XQS | | | | | | | | | 0.42 | | 0.57 | |
| | | | | | | YQS | | | | | | | | | | 0.30 | 0.61 | |
| | | | | | | TU | | | | | | | | | 0.35 | 0.25 | 0.14 | 0.17 |
| | | | | | | HOV | | | | | | | | | 0.39 | 0.22 | 0.56 | |

(b) M_{c5} , L_{c5} and Percent Time Yaw Control-Moment Command Exceeded Installed Limit, P_{NL}

| Case ¹ - Basic ² Conf. | N_V | Directional Parameters Varied | | | | Sub- Task ³ | Fixed Base | | | | | | | | Moving Base | | | |
|---|-------|-------------------------------------|----------|-------|--------------|---------------------------|------------|----------|-------------------|----------|----------|----------|-------------------|----------|-------------|----------|-------------------|----------|
| | | | | | | | Pilot A | | | | Pilot B | | | | Pilot B | | | |
| | | N_T | N_{cm} | T_y | $\delta\psi$ | | M_{c5} | L_{c5} | Sim. ⁴ | P_{NL} | M_{c5} | L_{c5} | Sim. ⁴ | P_{NL} | M_{c5} | L_{c5} | Sim. ⁴ | P_{NL} |
| D20 - PC1 | | -1 | 0.10 | 0 | 0 | XM | | | | | | | | | 0.40 | | 50 | |
| | | | | | | YM | | | | | | | | | | 0.28 | 0.48 | |
| | | | | | | XQS | | | | | | | | | 0.36 | | 0.48 | |
| | | | | | | YQS | | | | | | | | | | 0.30 | 0.53 | |
| | | | | | | TU | | | | | | | | | 0.30 | 0.29 | 0.45 | 13.20 |
| | | | | | | HOV | | | | | | | | | 0.38 | 0.26 | 0.54 | |
| D21 - PC1 | | -1 | 0.13 | 0 | 0 | XM | 0.39 | | 0.56 | | 0.40 | | 0.39 | | 0.38 | | 0.47 | |
| | | | | | | YM | | 0.28 | 0.48 | | | | 0.34 | | | 0.27 | 0.48 | |
| | | | | | | XQS | 0.50 | | 0.59 | | 0.39 | | 0.38 | | | | | |
| | | | | | | YQS | | | | | | 0.22 | 0.40 | | | 0.31 | 0.55 | |
| | | | | | | TU | 0.30 | 0.29 | 0.47 | 7.50 | 0.33 | | 0.31 | 1.00 | 0.28 | 0.26 | 0.39 | 6.70 |
| | | | | | | HOV | 0.32 | 0.22 | 0.47 | | 0.39 | | | | 0.36 | 0.25 | 0.50 | |
| D22 - BC1 | | -1 | 0.16 | 0 | 0 | XM | | | | | | | | | 0.40 | | 0.58 | |
| | | | | | | YM | | | | | | | | | | 0.28 | 0.50 | |
| | | | | | | XQS | | | | | | | | | 0.47 | | 0.58 | |
| | | | | | | YQS | | | | | | | | | | 0.29 | 0.57 | |
| | | | | | | TU | | | | | | | | | 0.34 | 0.26 | 0.44 | 1.10 |
| | | | | | | HOV | | | | | | | | | 0.39 | 0.22 | 0.52 | |

1. Wind simulation included mean wind, $U_m = 10$ kts. Thrust vector control available to trim longitudinal steady forces.
2. Symmetrical configurations - lateral derivative has same value as corresponding longitudinal derivative.
3. Key: XM, longitudinal maneuvering; YM, lateral maneuvering; XQS, longitudinal quick stop; YQS, lateral quick stop; TU, +180 deg turn-over-a-spot; HOV, precision hover.
4. Sim.: Simultaneous control moment usage, exceedance computations performed on the function $(|H_{c5}| + |L_{c5}|)$.

APPENDIX D

SUMMARY OF FLYING QUALITIES DATA AND PILOT COMMENTS FROM CALSPAN PILOT EVALUATIONS

Flying qualities data (pilot ratings and pilot-selected control sensitivities) for the flight simulator evaluations with Calspan pilot B are summarized in Table D-I. Another Calspan pilot participated briefly in the UARL program but did not perform flying qualities investigations. Calspan pilot B evaluated both lateral and longitudinal control test cases and height control cases. Turbulence effects, control lags and delays and control-moment limits were evaluated in the longitudinal and lateral control investigation (Table D-I(a)). The interactive effects of height velocity damping and thrust-to-weight ratio were evaluated in the height control study (Table D-I(b)).

Edited pilot comments from the Calspan pilot B evaluations are summarized in Table D-II. Comments for the longitudinal and lateral control test cases are shown in Table D-II(a) and those for the height control test cases are contained in D-II(b).

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с. Структурал конфигурацији - интериј дериват ве нас језо value as corresponding \log (ordinal derivative.

TABLE D-II

PILOT COMMENTS FROM CALSPAN PILOT EVALUATIONS

(a) Longitudinal and Lateral Control.

Case C11 EC1 $M_{\dot{\alpha}} = UL$ $L_{\dot{\alpha}} = UL$ $M_{\dot{\beta}} = UL$ $\sigma_{\dot{\alpha}} = \sigma_{\dot{\beta}} = 1.7$ $M_{\delta_e} = 0.447$ $L_{\delta_e} = 0.286$ PR 6

Control sensitivities - I did get adequate roll control; however, the configuration is such that it's difficult to stop it where you want, so you have to anticipate quite a bit. Adjusted sensitivities to give enough quickness of response so I would attempt to stop without having to anticipate as much. Then there was a tendency to oscillate so I finally compromised and accepted the sensitivities that I have now. Air taxi around the square - it's very difficult to remain over the spot on the ground, primarily because I'm behind the airplane or I'm overcontrolling, in attempting to maintain a position. It does seem that pitch response and bank angle response are quite good but the aircraft response in translation is very sluggish in both directions, both in trying to get it started and in stopping it. Once you get it started it's quite difficult to stop it with any precision at all. You approximate the task and that's about all you can do. There is a low level of precision here. If I concentrate very hard I can usually stay within the 16-ft square. Holding heading is no problem. There is some change in altitude, but not very much - maybe 7 or 8 ft. Quick stops - Don't really have any precision, you just have to make some pretty large inputs. Managed to do it a couple of times fairly well, but it was strictly a hit-or-miss proposition. Turning over a spot - That's a problem; the big difficulty is to stay within 10 to 20 ft of the center of the square. Hover - The ability to maintain position of a hover is quite poor as far as attitude and angular rates are concerned; however, it's not bad. As usual, have quite a bit of trouble laterally. Seems that I'm sliding back and forth all the time. The motion starts quite subtly, but once it starts it is difficult to stop. Overall evaluation - The major objectionable features are the sluggishness in response and control of the displacements. Favorable features include the fact that height control is pretty good, heading control is no problem and there are really no oscillatory tendencies at all in any direction.

Case C12 EC2 $M_{\dot{\alpha}} = UL$ $L_{\dot{\alpha}} = UL$ $M_{\dot{\beta}} = UL$ $\sigma_{\dot{\alpha}} = \sigma_{\dot{\beta}} = 0$ $M_{\delta_e} = 0.390$ $L_{\delta_e} = 0.320$ PR 7

Case C13 EC2 $M_{\dot{\alpha}} = UL$ $L_{\dot{\alpha}} = UL$ $M_{\dot{\beta}} = UL$ $\sigma_{\dot{\alpha}} = \sigma_{\dot{\beta}} = 1.7$ $M_{\delta_e} = 0.380$ $L_{\delta_e} = 0.320$ PR 9

With turbulence (C12) I would say, for all practical purposes, that the aircraft is unflyable. I can maybe keep it in the sky but the excursions are very large and I get the feeling I really don't have much control over the aircraft. I didn't get a chance to do anything in the way of maneuvering. All I was trying to do was to hover over a spot, and I wasn't able to do that. So I tried various gains on the cyclic both in pitch and roll and just didn't feel it was very good. I think it improved some when I went up to higher sensitivities, but not sufficiently that I would accept the airplane. This cut down the level or magnitude of the excursions, but still didn't think it was a flyable or acceptable airplane and I couldn't do the task. So then I flew it without turbulence (C12). Without the turbulence I was able to do the maneuvers to some extent. I get the impression that, even without turbulence, there are some external disturbances. These may be inadvertently, pilot-induced. Certainly it's a tremendous difference between turbulence in and turbulence out. With turbulence (C13) I would have to reject the configuration completely because at some point you probably will lose it, especially if the turbulence were any higher. Now, in smooth air, it did seem there was some lag in response to control inputs, about all axes, in spite of the fact that the height control is pretty good. I'd have to move the collective only a number of times. I think I was able to initiate the motion alright but precision of stabilizing velocities, etc., wasn't very good at all. I don't think my hover capability was real good although I did manage to make some turns in both directions and most of the time stayed within the square. There seems to be quite a bit of change in attitude, pitch primarily. Tried some quick stops. The airplane responds sluggishly; there seems to be a fair amount of lag required to either stop lateral motions or longitudinal motions. In turning over a spot, no real problem stopping on a heading. There is apparently no cross-coupling between the rudder and the cyclic. Probably would have been able to land this, at least in smooth air. In regard to secondary dynamics, in the higher rate maneuvers there was some cross-coupling. The major objectionable feature was the lack of precision with which I can initiate and maintain velocity and position over the surface. I did manage to do some things fairly good in hover, but that's about the only thing I was able to do fairly well.

Case C14 EC3 $M_{\dot{\alpha}} = UL$ $L_{\dot{\alpha}} = UL$ $M_{\dot{\beta}} = UL$ $\sigma_{\dot{\alpha}} = \sigma_{\dot{\beta}} = 0$ $M_{\delta_e} = 0.320$ $L_{\delta_e} = 0.365$ PR 8.5

Case C15 EC3 $M_{\dot{\alpha}} = UL$ $L_{\dot{\alpha}} = UL$ $M_{\dot{\beta}} = UL$ $\sigma_{\dot{\alpha}} = \sigma_{\dot{\beta}} = 1.7$ $M_{\delta_e} = 0.320$ $L_{\delta_e} = 0.365$ PR 10

Tried it with turbulence (C15) and found it completely unacceptable, probably a 10 rating. I flew it for a couple of minutes. In smooth air (C14) I tried quite a few things and I thought that might help but it didn't. It looks like lightly damped roll modes and I'm not sure about pitch. There were times where it almost felt like the airplane wanted to go on its own, but in any case didn't have precision of control. I had more trouble in roll than in pitch. Maneuvers not very successful. Regardless of control sensitivities, I never really felt I had good lateral control. I didn't have nearly as much trouble in pitch as in roll. Not able to establish any decent bank angle; very easy to overcontrol. I didn't like it, couldn't really stop or hover precisely. Not really able to stay within ground track limits. Quick stops - Not really very good at all; I tried some but seems like the airplane wants to take off, especially in the lateral quick stops. Turning over a spot - Didn't look real bad. It does seem that, once you get the airplane under reasonable control and get everything steadied out reasonably well, it can be held reasonably well.

TABLE D-II(a) (Continued)

Case C16 BC₁ $N_{C_m} = UL$ $L_{C_m} = UL$ $N_{C_n} = UL$ $\sigma_{u_C} = \sigma_{v_C} = 0$ $M_{\delta_e} = 0.321$ $L_{\delta_a} = 0.366$ IR = 3
 Case C17 BC₁ $N_{C_m} = UL$ $L_{C_m} = UL$ $N_{C_n} = UL$ $\sigma_{u_C} = \sigma_{v_C} = 1.7$ $M_{\delta_e} = 0.321$ $L_{\delta_a} = 0.366$ IR = 4.5

It was quite a bit more effort to try to do the task in turbulence (C17) but I was able to do that and even hover, say, fair. I could even keep within the 7-ft square. Lot of control activity in the turbulence, however. The configuration does seem to have reasonable stability and damping and the responses to control inputs appear to be reasonable with the particular gearings I chose. In smooth air the response to control inputs was fair. It does still seem that there are some lags in the initial responses to control inputs. I also did a fair amount of height control power inputs. I was able to establish displacements and velocities with reasonable precision in smooth air. Hovering capability was reasonably good. Could do the turns over a spot reasonably well. I really don't see anything strongly objectionable; the biggest thing probably are some lags in response to control inputs, but they are not really so bad. Could do it fairly well. Have some difficulty with bank angle, but it's probably me. So in smooth air I would say the aircraft was pretty good. I think performance in smooth air was satisfactory without improvement. In turbulence the work level certainly goes up quite a bit and maybe this is just a matter of proficiency. In turbulence the pilot compensation and workload are really fairly high.

Case C18 BC₁ $N_{C_m} = UL$ $L_{C_m} = UL$ $N_{C_n} = UL$ $\sigma_{u_C} = \sigma_{v_C} = 0$ $M_{\delta_e} = 0.370$ $L_{\delta_a} = 0.341$ IR = 3
 Case C19 BC₁ $N_{C_m} = UL$ $L_{C_m} = UL$ $N_{C_n} = UL$ $\sigma_{u_C} = \sigma_{v_C} = 1.7$ $M_{\delta_e} = 0.386$ $L_{\delta_a} = 0.402$ IR = 7

Flew this in smooth air first (C18) and I thought overall it was an excellent configuration. The only thing I noticed was a tendency to bobble the airplane a little in pitch. Whether there is lightly damped pitch oscillation here I don't know. Could have just been closed-loop. Noticed this particularly when I tried to make a fairly rapid attitude change. The control sensitivities seemed to be adequate in smooth air. I then flew short time in turbulence (C19) and felt the need to increase the control sensitivity to be able to offset some of the gusts. Not really sure which was better: without the higher sensitivity it seemed that I just didn't have sufficient control to keep the aircraft excursions small enough. On the other hand, with the higher gearings it did seem that I got into more high-frequency PIO's. Wasn't sure which to take, but it did seem that this gearing I chose in turbulence (C19) is better suited for precision control in doing the hover. The following comments are in smooth air. Response to control input seemed to be reasonable, although there were times when I felt it was a little sluggish, but I did seem to be able to stop the thing without needing a lot of lead, so maybe the damping is pretty good. The controllability of position and velocity seemed reasonable. Could hover very well. Could do turns over a spot very well. Very rarely went outside the 7-ft square. Could do the quick stops quite well although it did seem that I couldn't really generate high enough velocities with the control power I had. In other words, for the quick stop I would have expected to get a little higher speed going and make it much quicker, but this may be a function of the gearing I chose or it may just be a function of the dynamics of the aircraft. In any event, I was able to do all of the tasks with what I considered to be pretty good precision. The only possible objectionable feature is that the response, maybe initial response, to control inputs could be a little slow and possibly control power maybe was a little low. This may be my fault, going with the gearing I had. I don't really see that there is anything objectionable about it. In smooth air I certainly would rate it satisfactory without improvement for the task I was doing, with only negligible deficiencies or some mildly unpleasant deficiencies. In turbulence, I had quite a bit of trouble. The performance in turbulence certainly was not what I would consider very good so that the airplane would go into the deficiency-warrant-improvement category.

Case C20 BC₁ $N_{C_m} = UL$ $L_{C_m} = UL$ $N_{C_n} = UL$ $\sigma_{u_C} = \sigma_{v_C} = 0$ $M_{\delta_e} = 0.476$ $L_{\delta_a} = 0.673$ IR = 3

No comments due to defective recording.

Case C21 BC₁ $N_{C_m} = UL$ $L_{C_m} = UL$ $N_{C_n} = UL$ $\sigma_{u_C} = \sigma_{v_C} = 0$ $\tau_e = \tau_a = 0.3$ $M_{\delta_e} = 0.443$ $L_{\delta_a} = 0.600$ IR = 3

I didn't feel any great need to try a range of control sensitivities, so I left them where they were initially. Air taxi around the square - Response to control inputs seemed a little sluggish about all axes, but was able to stabilize and hold desired velocities. However, with these gearings the rates were generally rather small for fairly large inputs, but I felt comfortable with it. Some lag in initiation of the motion. Was able to stop the motion rather rapidly but it did take fairly large attitude changes to do it. Could actually overcontrol quite a bit and still be able to stop the motion pretty close to where I wanted it. Was able to come to a hover at the corners fairly well. Attitude changes required were fairly large, but mainly because I would wait quite awhile before I would try to stop it. Ability to remain within ground track was pretty good. Was able to hold heading well. Control deflections were very often on the fairly large side. Ability to hold heading wasn't bad at all. Control motions were fairly large. Turn over a spot - I thought my performance was very good as far as making turns and hovering; height control was no particular problem. Could initiate and maintain the turn rate. It seems to me it's strictly mechanical - you push the rudder in a certain amount, set up some kind of yaw rate and that's it. You can practically take it off the rudder and it will just stay there, and when you get within 5 or 10 deg of where you want to stop, just put in the opposite rudder. Doesn't seem to be any particular trouble as I can stop at a preselected heading very well. No wing tilt control used. Certainly I could establish hover quite well. Control was adequate for vertical maneuvers. I would probably say the most objectionable feature was that the aircraft wasn't very responsive. The few remarks feature is that I can do all the maneuvers with good precision.

TABLE D-II(a) (Continued)

Case CL12 BC4 $M_{Cm} = UL$ $L_{Cm} = UL$ $N_{Cm} = UL$ $\sigma_{u_g} = \sigma_{v_g} = 0$ $\tau_c = \tau_a = 0.6$ $M_{\delta_c} = 0.509$ $L_{\delta_a} = 0.237$ $PR = 5$

Once you establish a velocity while maneuvering, it can be held reasonably well. The problem was in initiating it in such a way that the pilot didn't oscillate or develop a PIO. Ability to stop precisely was a little problem because of the dynamics and the necessity for the pilot to reduce his gains so he didn't get into a PIO. I think there are times when the attitude changes are rather large, especially in pitch, but in fact the attitude changes are really fairly small. Would rate the ability to remain within ground track limits, to hold headings and to hold altitude as fair. Seemed like the altitude control was not quite as precise as desired, mainly because I was concentrating more on attitude inputs because of this tendency to get into a PIO. Did seem that I was making some fairly large control deflections in pitch and roll. To get large bank angle (10 deg max) rapidly and then try to stop it resulted in getting behind the oscillation. That part of the problem was strictly pilot-induced. For small corrections, didn't have that trouble at all. Really noticed this only in the large inputs and when I required large, high rates. Don't think I was able to accomplish what you might consider a quick stop maneuver. If I tried I just felt that I didn't know whether I could stop the motion, because I got into a pilot oscillation. Don't think there were any excessive attitude changes; was just cautious about getting the aircraft to move laterally and maintain reasonable rates so I could avoid oscillation. Ability to hold heading and altitude was somewhat degraded, I think mainly because I was more worried about stopping it. Turning over a spot didn't provide much trouble. Would be drifting a little but could make corrections. Only time I felt in trouble was when attitude rates got high. The objectionable feature was that large attitude changes had to be made slowly to avoid getting into an overcontrol situation and PIO. However, for small amplitudes and small corrections, and when things were fairly well stabilized, the precision of control wasn't bad at all. Special piloting technique is to make control inputs so as to stay away from oscillatory tendency.

Case CL13 BC4 $M_{Cm} = UL$ $L_{Cm} = UL$ $N_{Cm} = UL$ $\sigma_{u_g} = \sigma_{v_g} = 0$ $\tau_c = \tau_a = 0.1$ $M_{\delta_c} = 0.355$ $L_{\delta_a} = 0.341$ $PR = 2.5$

Tried higher lateral and longitudinal sensitivities and rapid, large amplitude maneuvers. With the higher sensitivities I could do a pretty good job although I seemed to be a little more oscillatory, so I decided to reduce the gains to roughly the initial values. Air taxi around the square. Response to control inputs seems a little sluggish. However, it's not really difficult to stabilize and hold desired velocities even though a little on the slow side. Ability to stop precisely not too bad. Seemed to be a relatively easy thing to stop precisely. Attitude changes may be a little on the high side. Ability to remain within ground track limits was quite good. Could hold heading and altitude quite well. Control deflections at times seemed to be on the large side with this gearing. For example, to get 5 deg of bank angle requires almost full throw, although I'm not hitting the tops. Didn't use any trim. Quick stops. With this gear ratio you don't really pick up very large velocities. After making an input it takes a little while for the velocity to pick up. To determine how much to lead it to stop didn't seem to be a very difficult thing. Ability to hold heading and altitude was quite good. Control motions required are substantial but manageable. Ability to hover over a spot was very good. Height control no problem. Pitch and roll control quite good. Ability to initiate and hold turn rates no problem and stopping on a pre-selected heading no problem. I was very happy with the precision of the hover, precision of the turns, ability to stop the motions; even though there are some lags in the system they were still quite noticeable. Control activity for vertical landing is probably fairly normal for a VSTOL airplane. The basic good feature is that the performance is quite good without excessive workload. No particular piloting techniques. I think it's acceptable and satisfactory, probably doesn't need any improvements unless you are looking for a highly responsive aircraft.

Case CL14 BC1 $M_{Cm} = 0.10\%$ $L_{Cm} = 1.12\%$ $N_{Cm} = 0.04\%$ $\sigma_{u_g} = \sigma_{v_g} = 0$ $M_{\delta_c} = 0.001$ $L_{\delta_a} = 0.11\%$ $PR = 10$

There is no question that this is an unacceptable configuration. I tried a range of longitudinal control sensitivities because I got into a longitudinal PIO which was so large and I was so far behind it that I in effect lost control. Increased the sensitivity; this seemed to improve things somewhat as long as I flew the airplane very tightly and with small amplitude displacements. Could be the pitch rate and attitude both couple in here to get me into trouble. If I got the aircraft moving forward pretty fast in trying to quick stop, it required very large pitch attitude to stop it. This is when I got into what appeared to be a very large amplitude situation where, in effect, I lost control. Did this about three or four times and went back to initial conditions. One can control the aircraft and do the maneuver task but you have to do it with small amplitudes and slow rates in pitch attitude. Once you get into large amplitude displacements and high pitch rates, then, in effect, control was lost. Would have to rate this an unacceptable configuration. It felt like control power was way down and so I just can't accept the airplane.

Case CL15 BC1 $M_{Cm} = 0.216$ $L_{Cm} = 0.248$ $N_{Cm} = 0.096$ M_{δ_c} and L_{δ_a} Unknown $PR = 5$

A pretty lousy configuration; not nearly as bad as the one I just had (CL14), but has similar characteristics, although the biggest problem with this one appears to be in controlling longitudinal position. Don't seem to have much control of forward and aft velocities or of being able to stop it with any degree of precision. Lateral control is not very good, but does seem to be a little better than longitudinal. Initial response to control inputs seems to be slow; however, once you get it started you do seem to have difficulty establishing a particular rate. It does seem to take a large pitch attitude change to get it moving and to stop it. Don't seem to have any idea when to make control reversals to keep it precise. Don't think my ground track was very good in any case. Always had some heading problems here because I'm very often inadvertently putting rudder in when I'm trying to turn or bank. Where it stopped in the quick stops was unpredictable. Can't stop it where I want it. Then trying to hold it was also a problem. Turning over a spot was quite ragged, errors were on the order of 10 or 20 ft from the center. Tried flying it very tightly but just wasn't really able to accomplish it. Performance

TABLE D-II(a) (Continued)

was quite poor. Trying to maintain a hover resulted in position errors on the order of 10 to 15 ft. Not sure I have adequate control for vertical landing. I suppose you might have some velocity, and just go ahead and land it, but trying to hit a spot is quite difficult. Lots of control activity. Objectionable features are the fact I just don't seem to know what kind of inputs to make to stop motions or initiate motions of the magnitude and the precision desired. No real special piloting techniques except that you try to second-guess or anticipate the inputs. Basically it's a very poor configuration from the standpoint of precision of control and performance.

Case CL16 BCL $K_{CL} = 0.116$ $L_{CL} = 0.249$ $M_{CL} = 0.096$ $\sigma_{CL} = 0$ $M_{CL} = 0.460$ $L_{CL} = 0.351$ $FR = 3.5$

I tried several control sensitivities. At the higher values, got into some PIO problems and some overcontrol problems, so I reduced them a little. There is some lag in the response to control inputs and it does take a fair amount of attitude change to get things moving, but it's not excessive. Can maintain velocities once I've established them as long as they are not too high. I do seem to run into some problems if I increase my gain and make larger inputs; in other words, if the rates are fairly high and it takes large amplitude attitude changes to stop the motion. Then I get into some over-control and oscillatory tendencies. For low and moderately low velocities I can stop fairly well on the corners. Performance on ground track wasn't too bad. Holding heading was OK. Quick stops - Wouldn't say these are really good quick stops. The main problem is that I relate the quick stop with high rate attitudes and large amplitude pitch or bank angles, where I get into trouble. So I've been a little hesitant to get it going too fast. I did get into some PIO laterally one time when I made a fairly rapid quick stop. Turn over a spot - That actually went very well as long as I had a good status rate of turn and not too fast. Was able to stay just about in the center of the spot most of the time. At the higher rates I went a little outside the square, maybe about 5 ft or so. I was fairly happy with the hover and turns, fairly happy with the low rates, both lateral and longitudinal, not too happy with the quick stop. Generally, it takes a moderate amount of concentration. I think I did induce some sort of lateral oscillation at times, especially when I felt I had to make some pretty rapid inputs.

Case CL17 BCL $M_{CL} = 0.268$ $L_{CL} = 0.336$ $M_{CL} = 0.228$ $\sigma_{CL} = 0$ $M_{CL} = 0.447$ $L_{CL} = 0.250$ $FR = 4$

Didn't do too much on the gearings. I seemed to be able to fly the airplane pretty well so I only changed the longitudinal sensitivity a little. Response to control inputs seems to be pretty fair. Was able to initiate motions but it's not as responsive as I would like it. As low as I maintain x and y to moderately low values, there is no problem in maintaining desired velocities. There is a lag in the response in u and v to control inputs, but the attitude changes required to get the airplane to move in the x and y direction seem to be only moderate. Pitch attitude changes and roll attitude changes to stop the motions seem what I would rate as moderate. Would prefer to have smaller changes required but it's not really too bad. Precision to stay over ground track was fair also. Did take some effort, but performance was not too bad. Holding heading was not a problem and altitude control was good and control reflections were moderate. Quick stops - Don't think it's as good as I would like to see it but it's really not too bad either. Does take pretty large attitude changes to perform a quick stop. Turn over a spot - Was fair to good; at least I didn't have to work too hard and I could probably stay within about 10 ft of the center of the square. No problems initiating and stopping the turn. Again I did not push the rate. In the hover the performance was pretty good. Did have to work fairly hard but not excessively hard to do a reasonable job, although you're always making inputs. Certainly adequate for vertical landing and control activity would be considered as moderate to moderately high. Some slight cross-coupling between lateral and longitudinal modes. I guess the only objectionable feature I could see was the lack of responsiveness of the airplane in the u and v velocities, ability to stop precisely, and the small lag in response of the aircraft to moderate control inputs. Also, the attitude changes are maybe a little higher than would like. You can see some improvements on the airplane. Desired performance requires moderate pilot compensation.

Case CL18 BCL $M_{CL} = 0.1$ $L_{CL} = 0.1$ $M_{CL} = 0.1$ $\sigma_{CL} = 0$ $M_{CL} = 0.447$ $L_{CL} = 0.250$ $FR = 5$

Tried several values of control sensitivity. Increased the sensitivity and didn't particularly like it because I got into some sort of pilot-induced oscillation, mainly in roll. There is still some lag in the response in the displacements and velocities of the aircraft. This was a sort of moderately difficult configuration to fly. Was able to do some things with pretty good precision, but it did take a lot of concentration. It did have a tendency to lag the control input, you had to anticipate stopping the motion of the aircraft laterally and longitudinally. Pitch response, roll response, yaw response all pretty good. Responsiveness in the initiation of motion and the stopping of the motion in the x and y directions was affected by lags in the system. Was difficult to stabilize and hold desired velocities. Then to try to stop it at any precise point was also somewhat difficult. I was able to hover pretty well, but it did take quite a bit of concentration. In doing so, there were some excursions in height but that was easily compensated with collective inputs. Height control was quite adequate; good damping in height. There is sort of a centreforce effect when you start turning, depending on the rate at which you turn. There is a tendency to drop down in altitude. Sure there is a loss of lift as it does require some noticeable power input to maintain altitude. Had a tendency to lose altitude in the turn over a spot. Also seemed to be power required when I made some rapid lateral and longitudinal displacements. As far as precision around the ground track, x and y was sort of rough, especially in the y direction. I was either too far ahead or too far behind the spot. Quick stops - It's a sort of a hit-or-miss proposition, although I managed to stop at the spot fairly well, but trying to hold it there was not easy. There did seem to be some fairly large control motions required. Turning over a spot - I think the ability to stay over the spot was only fair, I was always making corrections. Didn't make very fast turns. With these moderate turn rates I was able to stop it within about 15 deg of desired heading. Hover precision was fair, but I had to work fairly hard at it. Certainly adequate for vertical landing and control activity was almost constant. There were some cross-coupling effects between longitudinal motions and lateral or bank angles. I always had that problem. I guess the most objectionable feature is the fact that you do have to anticipate stopping of x and y motion and pitch attitude changes. Pitch attitude changes seem to be fairly large to maneuver. Overall, it does require moderate to considerable pilot compensation to do most of the tasks, especially the quick stops.

TABLE D-II(a) (Continued)

Case - C119 SC1 $M_{C_{D_{\text{min}}}} = \text{UL}$ $L_{C_{D_{\text{min}}}} = \text{UL}$ $N_{C_{D_{\text{min}}}} = \text{UL}$ $\sigma_{\text{UG}} = \text{UL} \approx 0$ $M_{\delta_{\text{e}}} = 0.500$ $L_{\delta_{\text{e}}} = 0.310$ $PR = 7$

This was not a very good configuration. I played around a little with the gearings, but the final values are essentially like the previous configuration. Even for relatively small amplitude displacements and rates, I just didn't think the precision of control and the precision of the task were adequate. Don't believe I ever felt I completely lost control, but there were times when very large excursions were obvious. Quick stops - I could stop it, but then I couldn't maintain position at the stopping point. Then trying to bring it back to hover was quite a problem. Could probably stop the turn on a heading within about 15 deg. Precision of hover was fair, but it did take a pretty fair amount of concentration. I would probably be able to land, although I'd have to be quite careful with it. Height control, however, didn't seem to be a big problem, although there was one maneuver where I think I let the altitude go all the way down to 20 ft. I guess the primary objection is the initiation of translational motion is sluggish and once you get the motion started it's difficult to stop it. Pitch control is certainly quite adequate. Lateral control seemed a little sluggish. The attitudes required to stop the airplane once you get it moving are fairly large, especially in pitch. Didn't see anything too favorable about the configuration. There is no pitch or lateral oscillation that is highly objectionable, so the damping in pitch and roll is pretty good. The problem is along the axes in translation and also the large displacements in bank angle and pitch attitude that are required to get the airplane to move and stop.

TABLE I(b) (Continued)

(b) Height Control

Case G11 $Z_{u_0} = Z_{u_1} = 0$ $T/W = UL$ $Z_{\delta_c} = 3.20$ $PR = 10$

Primary task was to evaluate ability to maintain height control while doing basic tasks. It's quite obvious you've absolutely no stability, no damping in height control, so the pilot starts off chasing altitude. The task is very, very severe. I was overcontrolling very, very much with the collective. I tried it again much more carefully and was actually able to get off the ground and establish about 50 ft and had pretty good control of altitude for a short time, maybe on the order of a minute or two, and was also able to hover over the spot at the same time fairly well, but was spending much time controlling altitude. So everything looked good; then I tried to start the maneuver. As soon as I did this, the altitude changed a little, so I tried to chase it with larger and larger collective inputs. Was going down to about 40 ft and up to about 80 or 90 ft. That's pretty poor. It was obvious that practically all my time would have to be devoted to height control and there would be very little time to do anything else with the aircraft. On the basis of height control alone, I would have to rate this configuration completely unacceptable. Control will be lost in some portion of required operation.

Case G12 $Z_{u_0} = Z_{u_1} = -0.25$ $T/W = UL$ $Z_{\delta_c} = 3.20$ $PR = 5$

Required a fair amount of monitoring of height control. The best I could do was to maintain altitude about 120 to 140 ft, but this took a fair amount of effort. I did all of the maneuvers. Didn't really think that these maneuvers were too bad. Some degrading might have occurred in performance due to time spent monitoring height control. Always shooting for 15 ft, but this time I doubled that on the average to 30 ft. Air taxi around the square response to controls really wasn't too bad. Was able to initiate motion in each direction. General comments - Essentially, I had a fair amount of monitoring on height control with rather large excursions. Say as much as 20 ft high and about 15 ft low from the nominal 50 ft that I'm shooting for. On the average, however, height control was about 120 ft. Required reasonable amount of monitoring. Didn't choose any control sensitivity, just accepted what was here as being reasonable. Could do all the maneuvers reasonably well. However, during the more rapid and larger amplitude maneuvers I had to monitor the height a little more carefully because it would tend to either climb or descend as I made these large amplitude inputs. Most objectionable feature would be the height control; I would certainly like to have it be better. Favorable feature, I think, was the fact that, in spite of height control, I was still able to do all maneuvers reasonably well.

Case G13 $Z_{u_0} = Z_{u_1} = -0.35$ $T/W = UL$ $Z_{\delta_c} = 3.20$ $PR = 3.5$

Control sensitivity - Finally chose this one, which is a little lower gain than would have really liked from a standpoint of initial response. With higher sensitivities, got into other little problems like a tendency to overcontrol some, so I finally backed off. Taxi around the square response to inputs was fair. Ability to stabilize and hold desired velocities was fair. Could stop and come to a hover at the corners reasonably well, although again it takes fairly large and rapid inputs to stop. It does take fairly large pitch and roll attitudes; the bank angles are usually less than 5 deg and in pitch less than 5 deg. However, was able to maintain ground track quite well and no problem in holding heading because you just keep your feet off the rudders in effect, and the friction holds it once you establish that you have no rate of turn. Altitude control - Spent some time on it; could maintain altitude if I wanted to within 15 ft for normal maneuvering. Not true when I went into large amplitude, very rapid or at least attempted to make very rapid inputs to establish higher rates. Here height control problem became a little more obvious. Quick stop - Could stop quickly but, considering that rates are fairly low, the attitude changes appeared to be fairly high. So attitude control doesn't seem to be much of a problem; height control a little bit of a problem, definitely noticeable that you do have to spend some time on it. Can initiate and hold turn rates without problem; can stop on preselected heading even at very high rates. Didn't use any of the wing tilt control. Precision hover - Vertical landing - Was able to establish and maintain precise hover quite well, a little skidderish but not really too bad; could generally stay well within the 7-ft square. The dynamics of one axis did not affect the evaluation of another. Overall evaluation - Somewhat objectionable feature was that you have to look at the height control, but it really wasn't that big a feature. Was reasonably satisfied that I could meet my criterion of 15 ft, but to do that it requires maybe a little more time and cross reference than is desirable. Favorable features - The fact that I can do all the maneuvers with reasonable precision in a fairly good way. No special piloting technique.

Case G14 $Z_{u_0} = Z_{u_1} = -0.175$ $T/W = 1.00$ $Z_{\delta_c} = 4.20$ $PR = 3.5$

Control sensitivities - Added a little sensitivity. It seemed to be a little better. I would say generally this was a fair configuration. Air taxi - The precision of control is still not really as good as I would like it. The small sensitivity change helped some. Still get the feeling there are appreciable lags from collective input and in stopping the rates of descent or rates of climb I can find a fairly well stabilized altitude with some effort. It takes several power inputs and cross-checking between the display and altimeter to find it. After a while you sort of mechanically put the power in and get a rate of descent. To get the rates of descent under control, you make a fairly large input and then hold it for a second or two and take part of it out again and then cross-check the altimeter and display. It seemed to me that maybe 2 ft/sec is about as high as I would like to see or like to go with this thing. One time I had a fairly high rate of descent going and got down to about 12 ft on the altimeter. Was wondering whether I would be able to stop the rate of descent before touching down. Touchdown is about 9 ft. I still think there is some limitation here. It's probably a combination of limited thrust available plus aerodynamic damping and artificial damping. I can't differentiate; it's a combination, I think. As far as height control is concerned, you could do a fair job of flying the airplane. You can get adequate performance; is it satisfactory without improvement? Maybe you have some moderate pilot compensations to get the precision you want. There are again limits to how fast you can go up and down and still be able to control the rate of climb or the rate of descent. Precision of control, again, does take a certain amount of pilot effort to get the proper power setting, so frequency of collective input is maybe a little higher than you would like.

TABLE D-1(b) (Continued)

Case CH5 $Z_{u_2} = 0$ $Z_{u_3} = -0.35$ $T/W = 1.02$ $Z_{\delta_c} = 8.00$ $FR = 4$

The hover performance was reasonable. Tried quite a few control sensitivities. I was having some lags in height control response to collective which I could improve by increasing the sensitivity. I had a tendency to then overcontrol, so I went back toward the lower sensitivity. I wasn't too happy with the precision of height control. Had to spend a fair amount of time at it and almost invariably when I did I had trouble trying to maintain my position over the spot. However, it was not really that horrendous. It was one of those configurations that, if the rates of change in height were kept to a low level, I was able to establish a steady-state height reasonably well, but again with quite a number of collective inputs. At the higher rates, did overcontrol quite a bit. When I reduced rates to fairly low levels, maybe a half-foot per second or something in that order, it gets reasonable as far as precision, with some effort you maybe can establish a hover height about 25 ft. It's certainly controllable. I can get adequate performance with tolerable workload. I would think you should improve this some; I wasn't too happy with the precision of control only because it took quite a bit of effort, a lot of collective inputs to finally establish a steady-state hover height. I would probably think it's at least a moderate compensation required. I'm not really sure whether I ran out of thrust. Had the feeling that possibly at the higher rates it took a large amount of collective to stop the rate of sink.

Case CH6 $Z_{u_2} = Z_{u_3} = -0.05$ $T/W = 1.05$ $Z_{\delta_c} = 3.20$ $FR = 6$

Selection of the gearing was predicated primarily on reducing overcontrol tendencies. Ended up I think with the minimum gearing available. I had gone up fairly high with it; however, there is a very strong tendency to overcontrol, so I was going up and down like a yo-yo for a while. I was spending a fair amount of time on the height control when I was trying to be precise with it; that deteriorated the performance on the X-Y plane. The overall impression is that it is not a very good configuration. I suspect that it's a damping problem primarily, but I couldn't care less whether it is damping or the fact that I may have lags in the power application, or that there is a lack of excess thrust available. The end result is the same. The precision of height control is just not there. I could probably land it as long as I can keep the rates down. Have to work pretty hard, though, to establish exactly 20 ft or exactly 40 ft within, say, 2 ft; that's a fairly difficult task. It does warrant improvement. It has very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation.

Case CH7 $Z_{u_2} = Z_{u_3} = -0.175$ $T/W = 1.05$ $Z_{\delta_c} = 1.51$ $FR = 5.0$

I didn't change the sensitivities on collective, just accepted what I had, mainly because it seemed adequate. I did a little better in hover, but I'm still having tough time flying longitudinal and lateral modes so I concentrated more on the hover in evaluating the height control. It's a matter of rates, I think. If I keep the rates reasonably low, I have some precision. If I try to speed up the response, I'm way behind the airplane in trying to recover it. I think the objectionable features are the lead time required in stopping the motion once you get it moving, the lag in getting some noticeable movement when you make the input and the fact that the precision of control in all axes was rather poor. If I set up high rates of descent and high rates of climb, then the precision just isn't there. You get an overshoot of at least 10 ft or more in the climb direction. I'm a little more hesitant to allow it to drop below 20 ft so I tend to make sharper, faster, larger inputs when the rate of descent is fairly high and I'm approaching 20 ft. It's like bare-bare control, you just put it in and say take some of it out because you know you probably have overcontrolled. Think it is controllable. Adequate performance with a tolerable workload? Not if you're talking about the overall task.

Case CH8 $Z_{u_2} = Z_{u_3} = -0.05$ $T/W = 1.05$ $Z_{\delta_c} = 1.51$ $FR = 3$

It is still not very good, but I managed to hover a times almost within the square, which is pretty good. The same things bother me in longitudinal and lateral control: the lags, the turbulence, possibly the gearing is involved in there also. On the precision of vertical control, I was able to go down to 20 ft and hold it there while I attempted to do some maneuvers, went back up to 40 ft and hit it fairly well. For long periods of time the height control required no attention. Also attempted some high rates of descent and climb. The time that I have to concentrate on the height control is fairly minimal. Precision of height control was pretty good and the fact that you can pretty much set the collective and the height stays fairly close to where you put it, certainly within the 5 ft; that's pretty good. It seemed that there was always somewhat of a lag, but I think that's probably built into the altimeter. Possibly some of this hunting for the proper collective position may be caused by that lag in the altimeter. Only minor or minimal pilot compensation required.

Case CH9 $Z_{u_2} = Z_{u_3} = -0.05$ $T/W = 1.10$ $Z_{\delta_c} = 5.10$ $FR = 7.5$

I played around with the collective sensitivity quite a bit and was not able to find anything I liked. As I increased the sensitivity, I overcontrolled very badly. I had started out with the sensitivity to the minimum position on the lever and went up just a little, but that gave me all kinds of trouble. I picked something halfway between. I was still having troubles so I finally settled on having minimum sensitivity and that still gave me the same kinds of problems I had on the previous configuration (CH8) except more accentuated. To get the thing moving it seems to take quite a bit of thrust; once you get it moving, though, to stop it takes quite a bit of collective change so I suspect we have some degradation in the height damping, plus the fact that possibly we have low excess thrust available for height control. End result is that performance on the tasks, longitudinal and lateral, was quite bad. Didn't even try the lateral displacements; I was having enough trouble with pitch.

TABLE D-II(b) (Concluded)

Used a good portion of time just trying to keep the airplane at proper altitude or at least trying to stay close to the 20 ft or 40 ft altitude. I was overshooting at least 10 ft. Have a tendency to fly tighter when I'm going down than when I'm going up. Main objection was that I did not have precision of height control. I think there were times when I did manage to have the power lever just about right but then every time you maneuver the airplane to some extent you do have quite a bit of activity with the collective.

Case CH10 $Z_{\omega_a} = Z_{\omega_c} = -0.125$ $T/W = 1.10$ $Z_{\delta_c} = 1.51$ $PR = 5$

The initial control sensitivity on the collective was a little high and I overcontrolled very badly, so I cut the sensitivity down some. Was having more problems with hover than anything else on this configuration. Seems to be substantial lead required both in pitch and roll but it's more obvious in the pitch axis. The dynamics are also a problem. I had to make reasonable number of collective inputs to maintain 40 ft. However, it seemed to be a reasonable task. On the other hand, when I started to make climbs and descents to about 20 ft and back up to 40 ft, still had a tendency to overcontrol with the collective because there seemed to be a lack of thrust or there was a lag in the response of the thrust; either way you would get the same effect. Overall performance of the tasks was quite poor, especially the hover; I really had trouble with that. As long as I did things at reasonably low rates, I could manage to do the task. If I tried to push the airplane and force it to respond at higher rates, then everything seemed to go to pot. I don't really think I could do a quick stop with this thing too well. I didn't try any turns over the spot. Precision of hover, I thought, was quite poor and I had difficulty in establishing reasonable rates of descent and climbs so I could stop the height exactly where I wanted it. I think it was probably adequate for vertical landing as far as height control was concerned, but I'm not too sure about being able to hit a spot with any degree of precision. Control activity was quite large; I was continuously making inputs. Overall, there wasn't anything I particularly liked about it, but I thought it was flyable with a fairly large amount of effort. It takes quite a bit of concentration.

Case CH11 $Z_{\omega_a} = Z_{\omega_c} = -0.175$ $T/W = 1.10$ $Z_{\delta_c} = 6.30$ $PR = 3$

Don't have the feeling I have very precise control of the aircraft; however, I managed to keep reasonable control. It's just concentrating on height control that's a problem. By using low rates for take-off and changing altitude by 20 ft from 40 ft to 20 ft and back to 40 ft, did seem to have reasonable precision within about 1 or 2 ft. However, I did do a couple of maneuvers where I increased the rates fairly high and did have some overshoot problems. Got the impression that it was because I needed more collective displacement than I would normally like to use; it seemed I was using quite a bit of power. The excess power available is not as much as I would like. I don't think it was associated with damping per se because generally I could stabilize pretty well at 40 ft and 20 ft with just a moderate amount of hunching. Objectionable feature - I think it was just at the higher rates; too much collective displacement was required. Favorable features were that, by keeping the rates reasonably slow, I was able to have pretty precise control of altitude. No special piloting techniques except that, because of lags in the lateral and longitudinal dynamics, you have to lead the power application if your rates of descent or rate of climb get too high. It's hard to say exactly what those rates are, but if you're going to change 20 ft in more than about 30 sec, then you may get into some power application problems. I suspect it was probably lack of sufficient excess thrust available for control.

APPENDIX E

CONTROL-MOMENT EXCEEDANCE PLOTS FOR THE MANEUVERING SUBTASK

Pitch, roll, yaw and height control power exceedance data computed for a range of reference moment levels are contained in this Appendix. Initially, exceedance plots are present for pitch, roll and combined pitch and roll control moment data measured during the maneuvering subtask. The effects of turbulence intensity, aircraft speed stability and drag parameter, level of aircraft pitch and roll dynamics, control lags, rate and control coupling, and independent thrust-vector control can be seen in these exceedance data. The change in thrust-usage exceedance values with height velocity damping are presented next, and the final figure in this Appendix contains the yaw control-moment-usage exceedance results. In general, the effects of the different parameters examined on control-power usage, as defined by the exceedance data in this Appendix, are consistent with the effects noted (for the maneuvering subtask) by comparing the 5-percent exceedance levels.

| RMS TURBULENCE INTENSITY, FT/SEC | 3.4 | 5.8 | 8.2 |
|-------------------------------------|-----|-----|-----|
| SYMBOL | ○ | □ | △ |

CONFIGURATION BC1 $M_{jg} \approx -L_{jg} = 0.33$ MANEUVERING SUBTASK

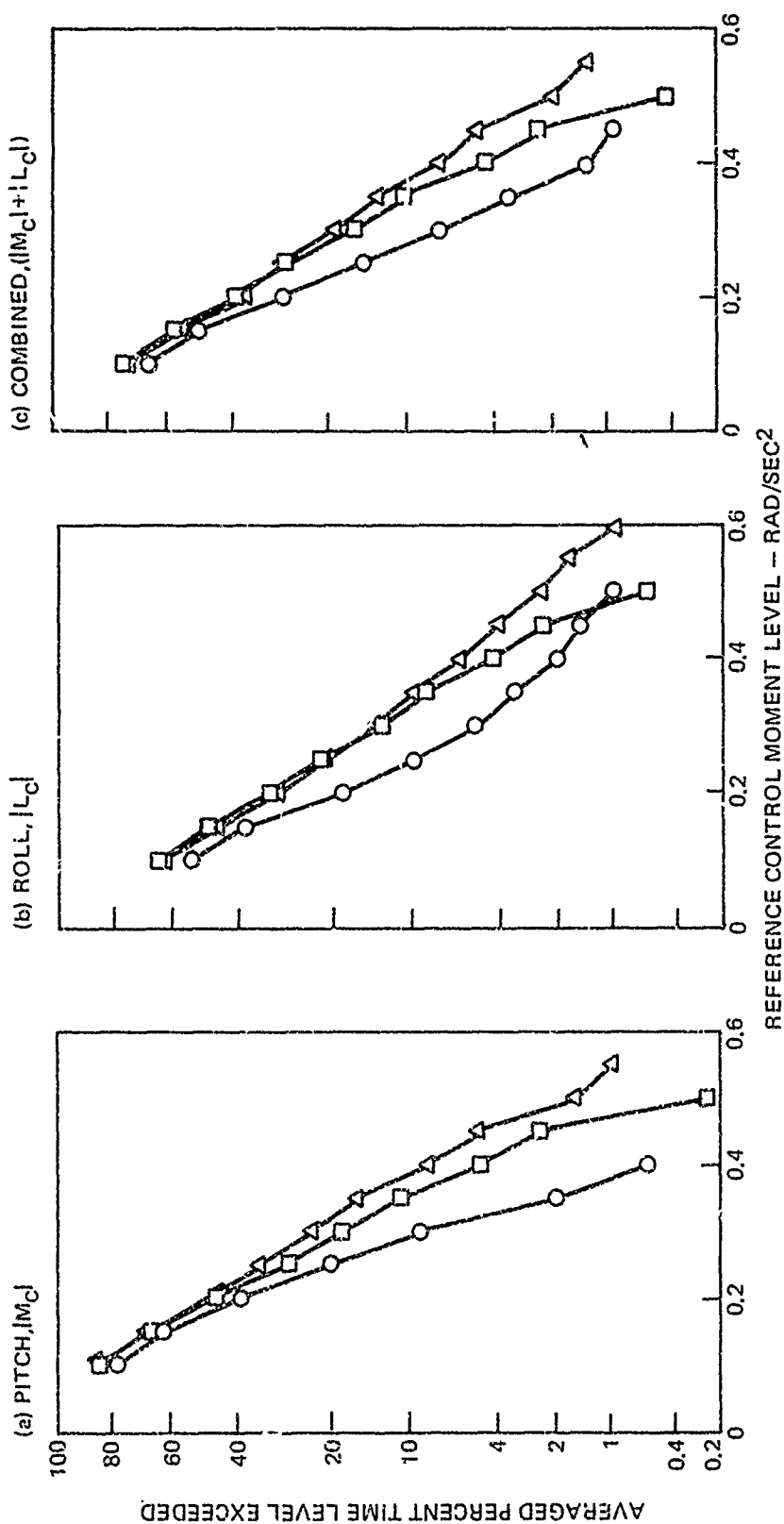


FIGURE E-1. Effect of Turbulence on Exceedance Results for a V/STOL Configuration with Small Response to Turbulence

| RMS TURBULENCE INTENSITY, FT/SEC | 3.4 | 5.8 | 8.2 |
|-------------------------------------|-----|-----|-----|
| SYMBOL | ○ | □ | △ |

CONFIGURATION BC6 $M_{0.9} = L_{0.9} = 1.0$ MANEUVERING SUBTASK

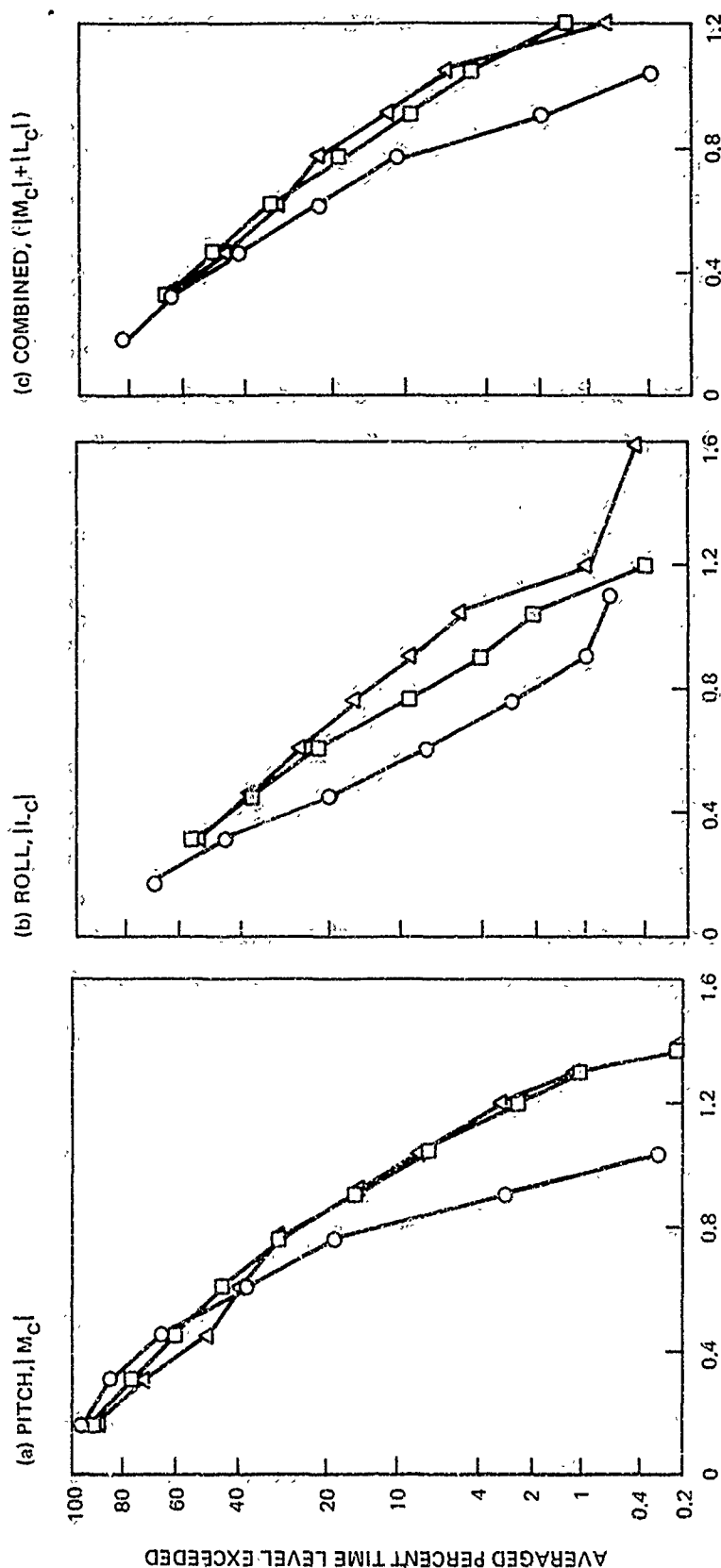
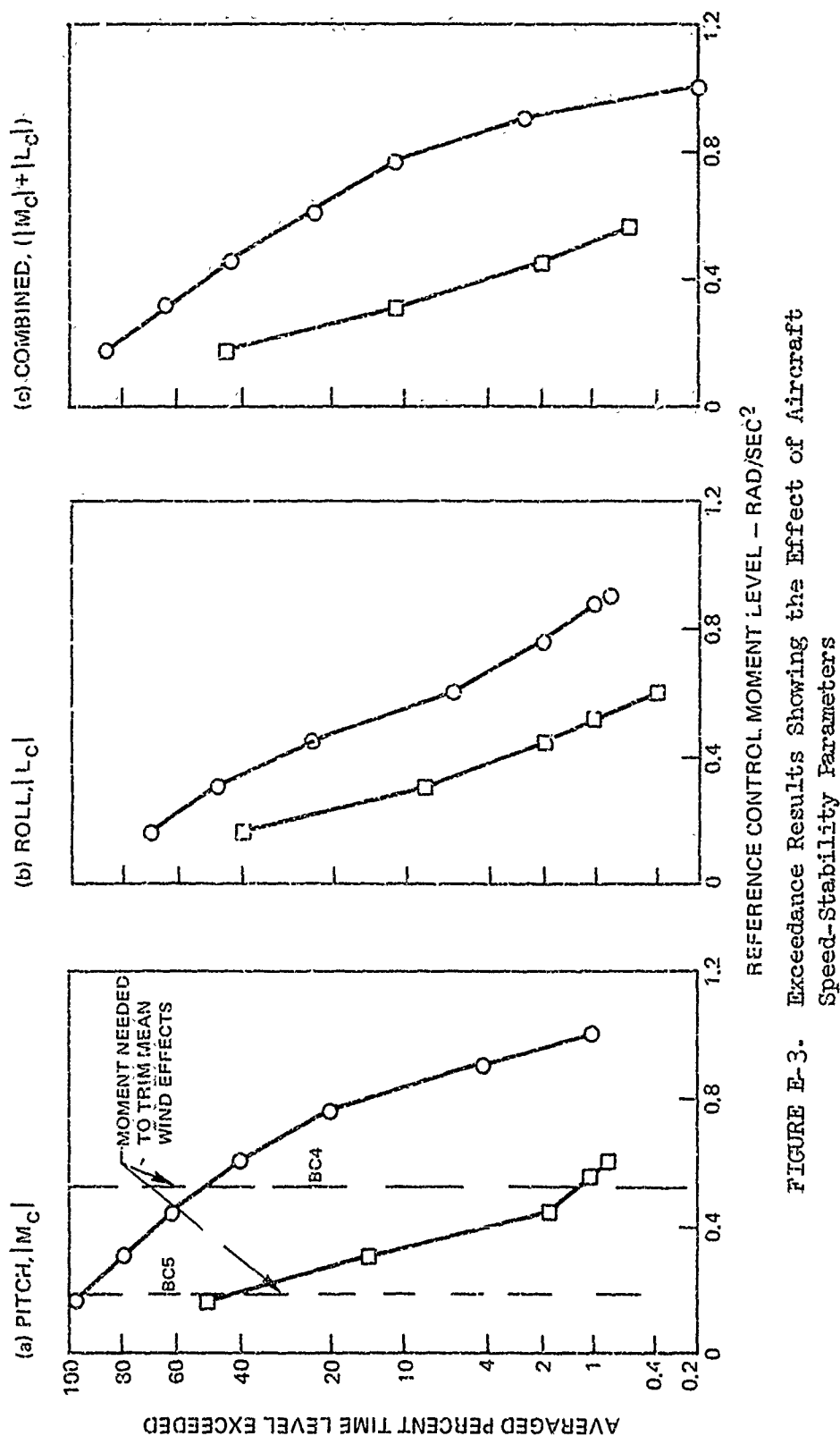


FIGURE E-2. Effect of Turbulence on Exceedance Results for a V/STOL Configuration with Large Response to Turbulence

| BASIC CONFIGURATION | BC5 | BC4 |
|---------------------|------|-----|
| $M_{U9} = -L_{U9}$ | 0.33 | 1.0 |
| SYMBOL | □ | ○ |

$\sigma_{U9} = \sigma_{V9} = 3.4 \text{ FT/SEC}$ MANEUVERING SUBTASK



| BASIC CONFIGURATION | BC1 | BC5 |
|---------------------|-------|-------|
| $X_u = Y_v$ | -0.05 | -0.20 |
| SYMBOL | ○ | □ |

$\sigma_{u_g} = a_{u_g} = 3.4 \text{ FT/SEC}$ MANEUVERING SUBTASK

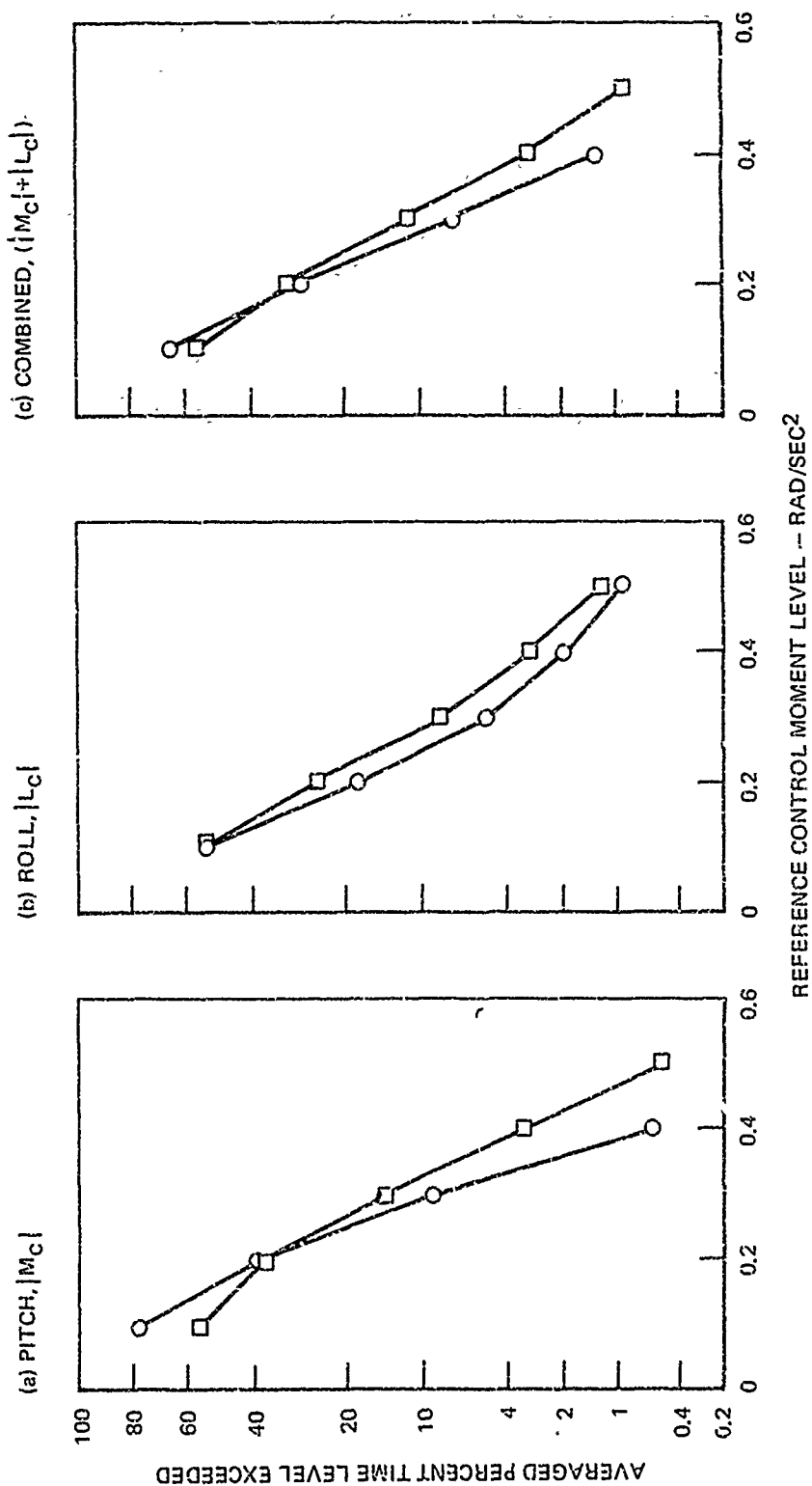


FIGURE E-4. Exceedance Results for V/STOL Configurations Having Different Drag Parameters

| LEVEL | 1 | 2 | 3 |
|---------------------|-----|-----|-----|
| BASIC CONFIGURATION | BC4 | BC2 | BC3 |
| SYMBOL | ○ | □ | △ |

$M_{Ug} = -L_{Ug} = 1.0$ FOR BC4, BC2, BC3 $U_{Ug} = 3.4$ FT/SEC MANEUVERING SUBTASK

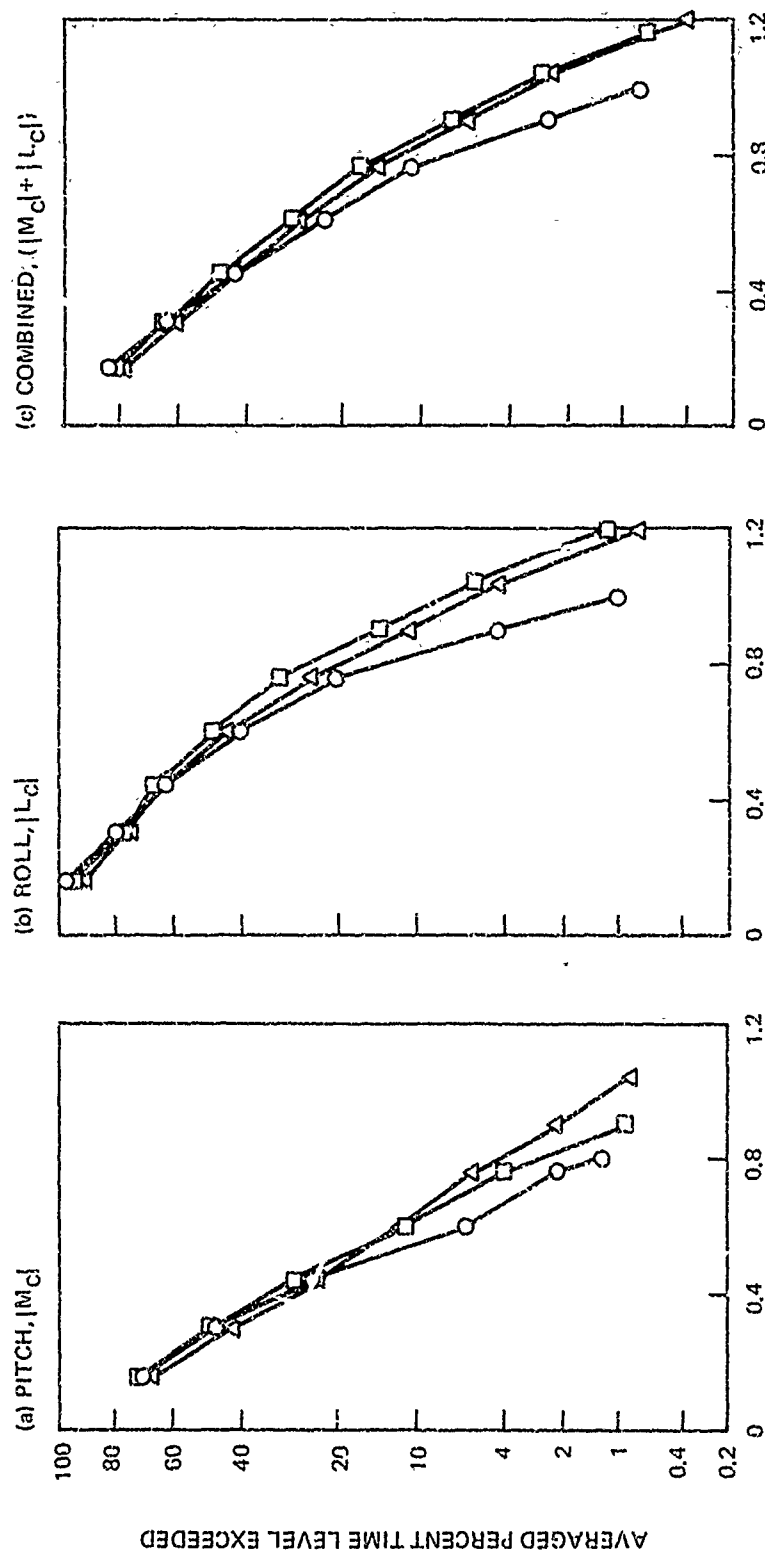


FIGURE E-5. Exceedance Data for Three V/STOL Configurations Exhibiting the Three MIL-F-83300 Levels of Flying Qualities

| CONTROL LAG | 0 | 0.3 | 0.6 |
|-------------|---|-----|-----|
| SYMBOL | ○ | □ | △ |

CONFIGURATION 3C1 $M_{Ug} = -L_{Ug} = 1.0$ $\sigma_{Ug} = \sigma_{Vg} = 3.4$ FT/SEC MANEUVERING SUBTASK

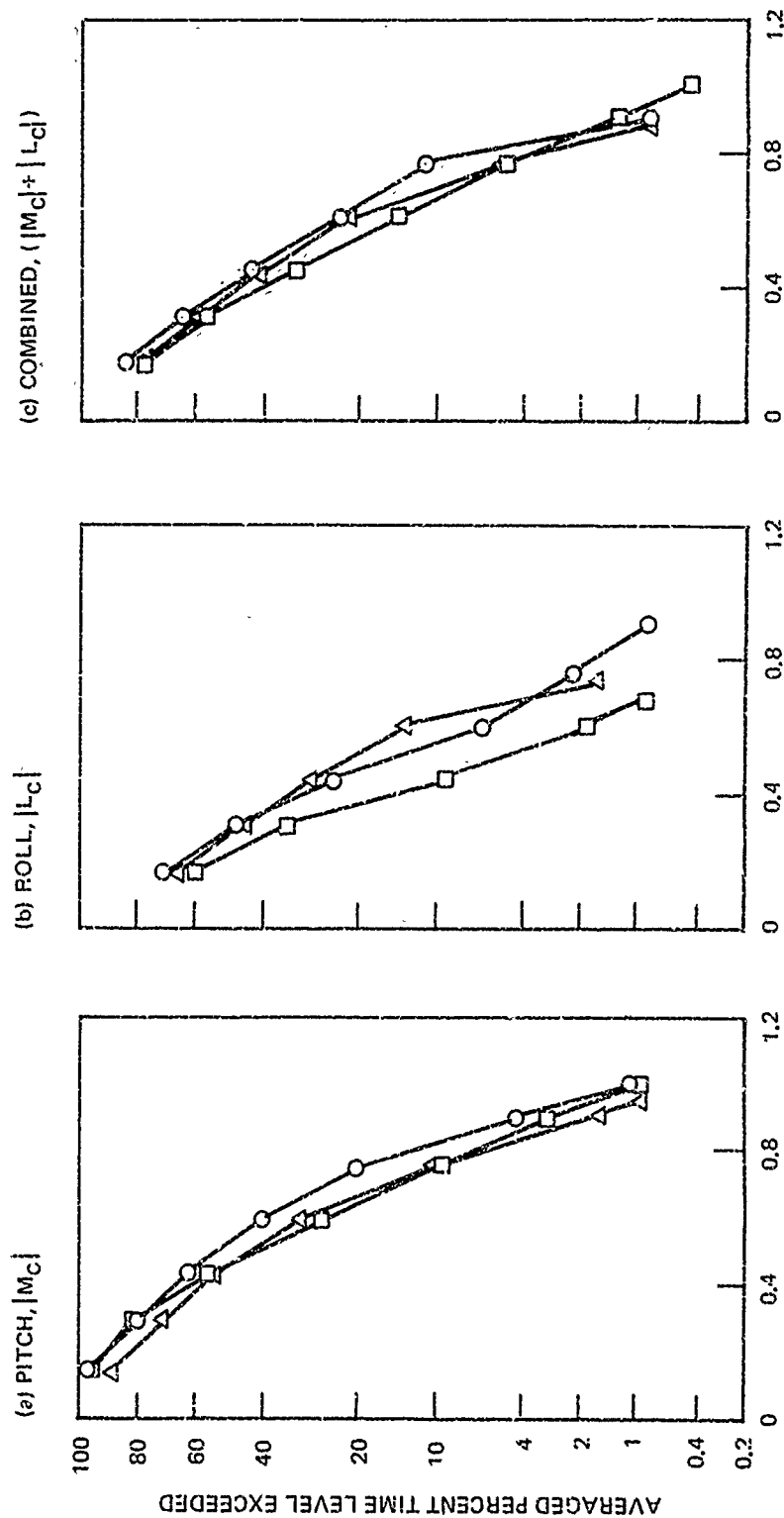


FIGURE E-6. Effects of Control Lags on Exceedance Results for a Configuration with Moderate Response to Turbulence

| $M_{\delta_2}/L_{\delta_2} = -M_{\delta_e}/L_{\delta_e}$ | | 0 | | 0.25 | | 0.50 | |
|--|--|----|----|------|----|------|----|
| SIMULATOR MODE | | FB | MB | FB | MB | FB | MB |
| SYMBOL | | ○ | ● | □ | ■ | △ | ▲ |

CONFIGURATION BC1 $\sigma_{u_g} = \sigma_{v_g} = 3.4$ FT/SEC $M_{u_g} = -L_{u_g} = 0.33$ MANEUVERING SUBTASK

(a) $M_p = -L_q = 0$

(b) $M_p = -L_q = 2$

(c) $M_p = -L_q = 4$

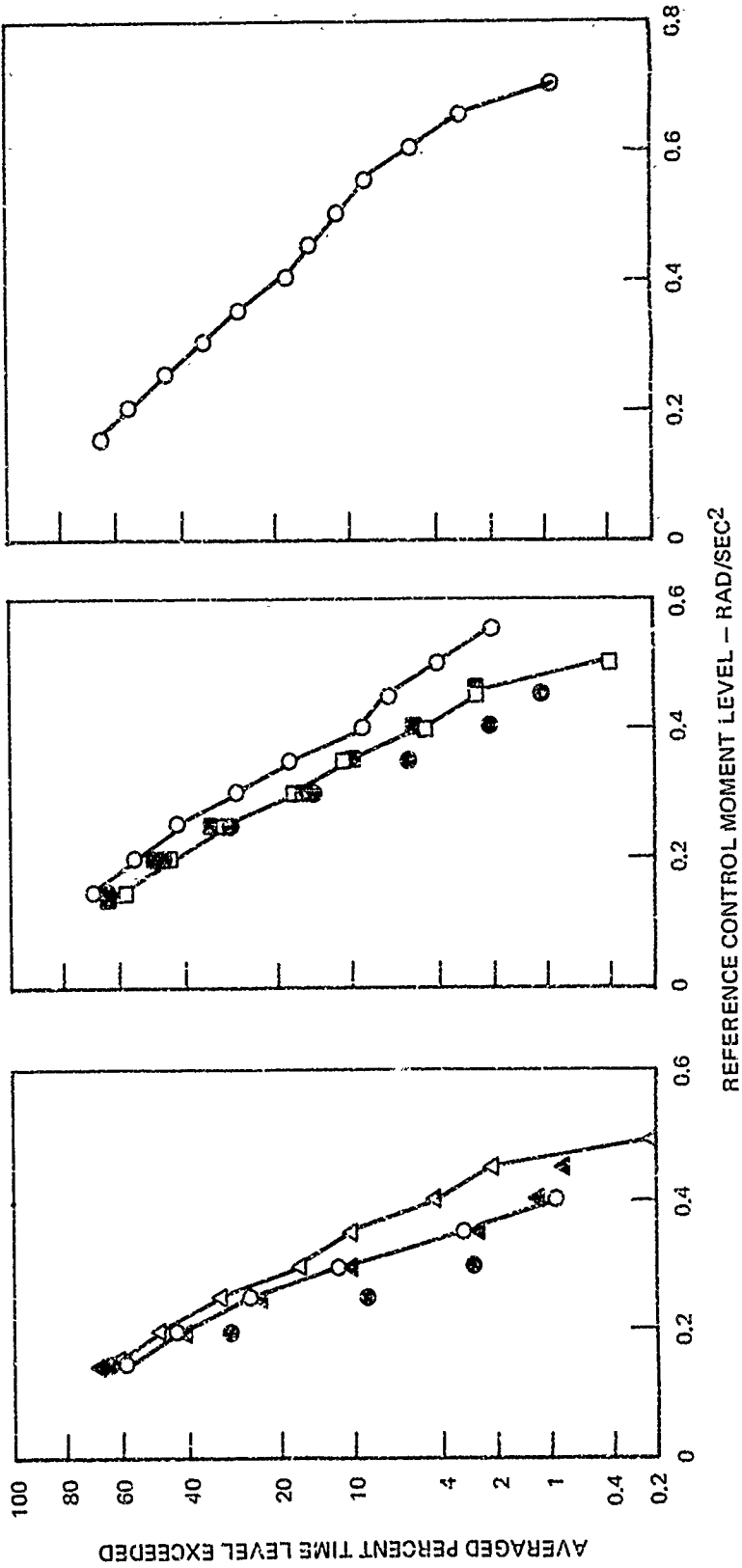
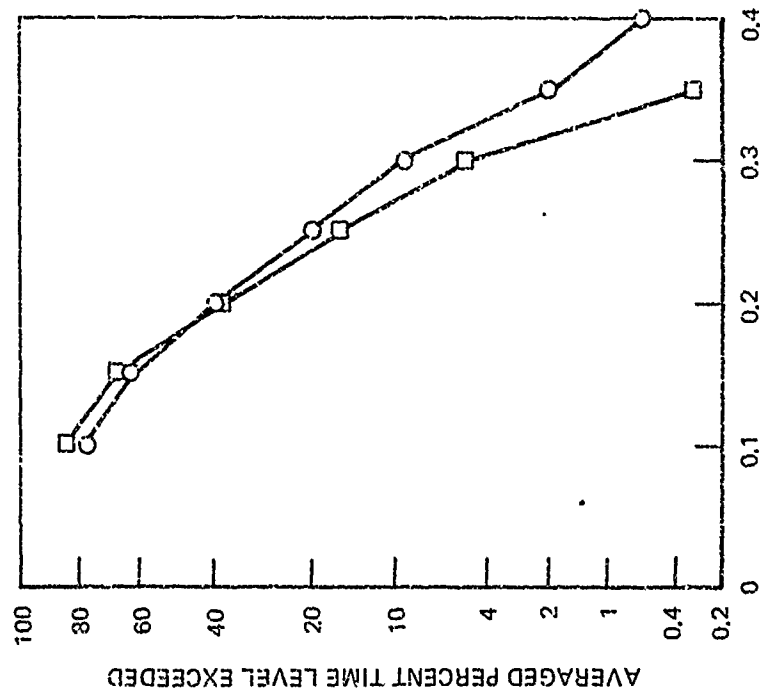


FIGURE E-7. Effect of Rate and Control Coupling on Pitch Exceedance Results

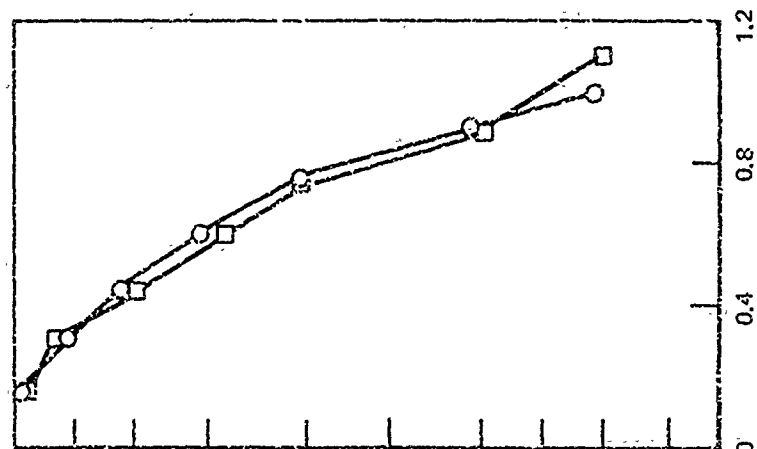
| TYPE OF POSITION CONTROL | CONVENTIONAL | INDEPENDENT THRUST-VECTOR CONTROL |
|--------------------------|--------------|-----------------------------------|
| SIMBOL | ○ | □ |

FIXED BASE MANEUVERING SUBTASK
 THUMB-SWITCH THRUST-VECTOR CONTROL, $\dot{\gamma} = 20$ DEG/SEC, AND CONTROL-STICK
 ATTITUDE CONTROL FOR INDEPENDENT THRUST-VECTOR CONTROL

(a) CONFIGURATION BC1



(b) CONFIGURATION BC4



REFERENCE PITCH CONTROL MOMENT LEVEL -- RAD/SEC²
 FIGURE E-8. Comparison Between Pitch Control-Moment Exceedance Data for
 Independent Thrust-Vector Control and Conventional Position
 Control

| LEVEL OF Z_{WT} | 0 | -0.25 | -0.50 |
|-------------------|---|-------|-------|
| SYMBOL | O | □ | △ |

$$Z_{WT} = Z_{W\theta} + Z_{W\omega} \text{ WHERE } Z_{W\theta} = Z_{W_s}$$

$$T/W > 1.15$$

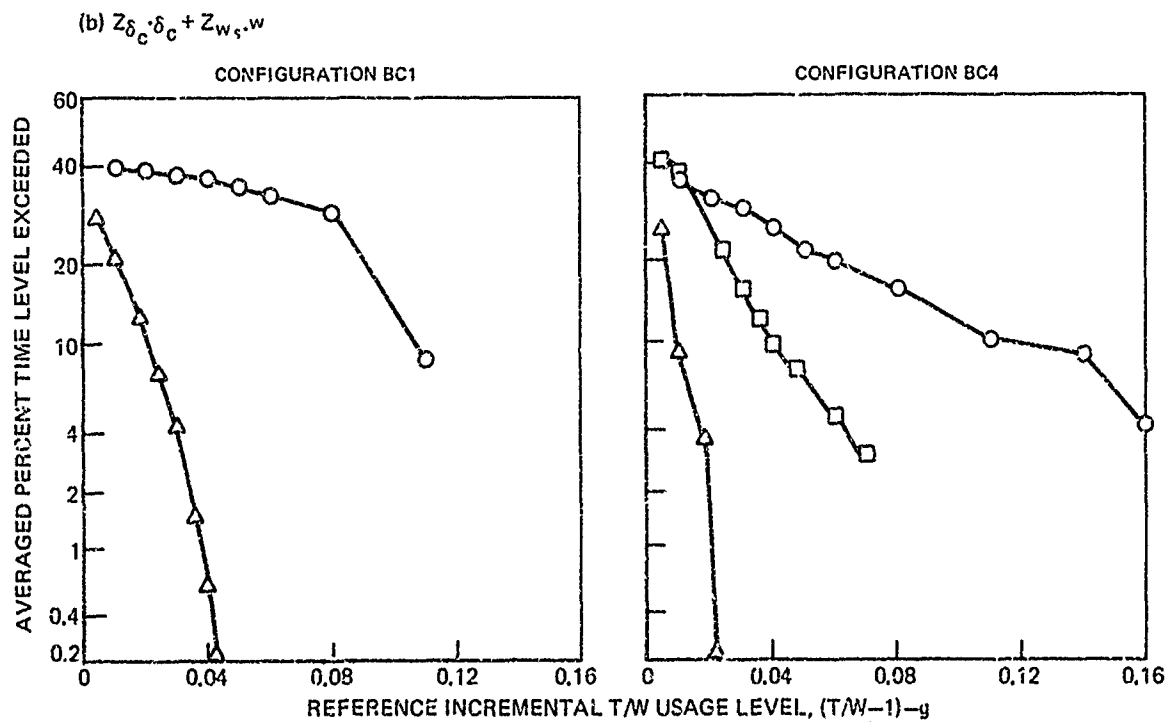
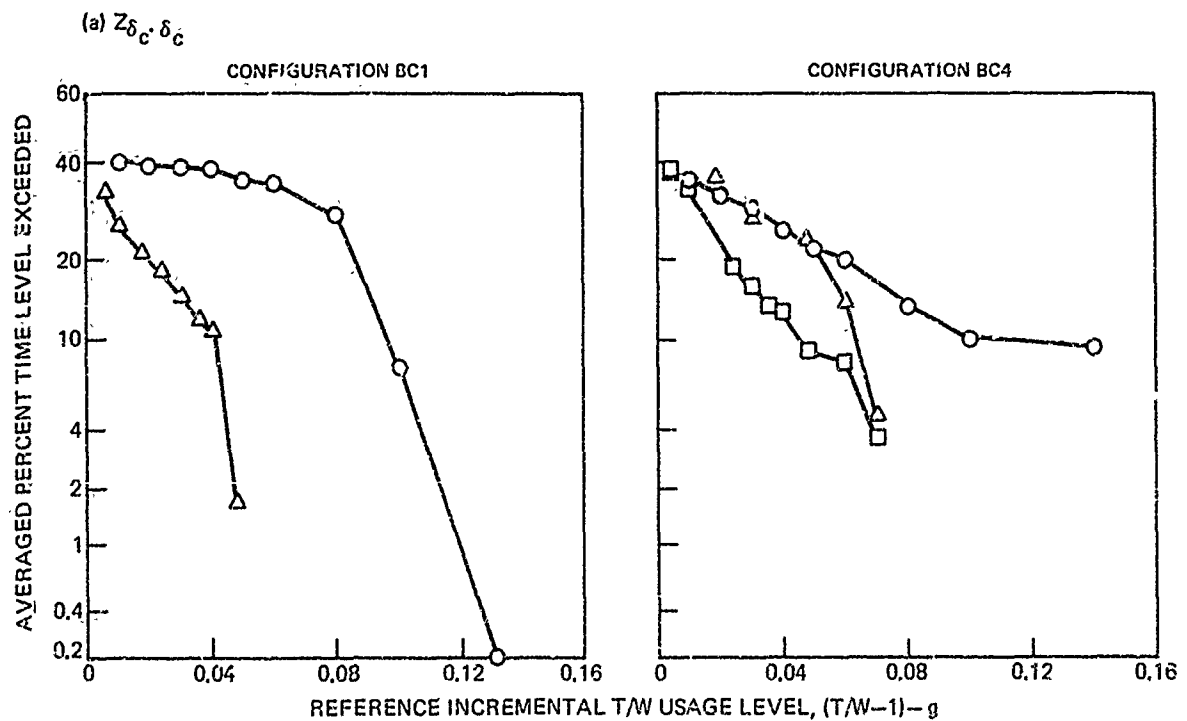


FIGURE E-9. Effect of Z_{WT} on Incremental Thrust, $(T/W-1)$, Exceedance Results Computed for Increased Thrust Commands

| FIRST ORDER CONTROL LAG, T_ψ | | 0 | 0.3 | 0.6 |
|--------------------------------------|--|---|-----|-----|
| SYMBOL | | ○ | □ | △ |

TURN SUBTASK CONFIGURATION BC1 $N_V = 0.005$

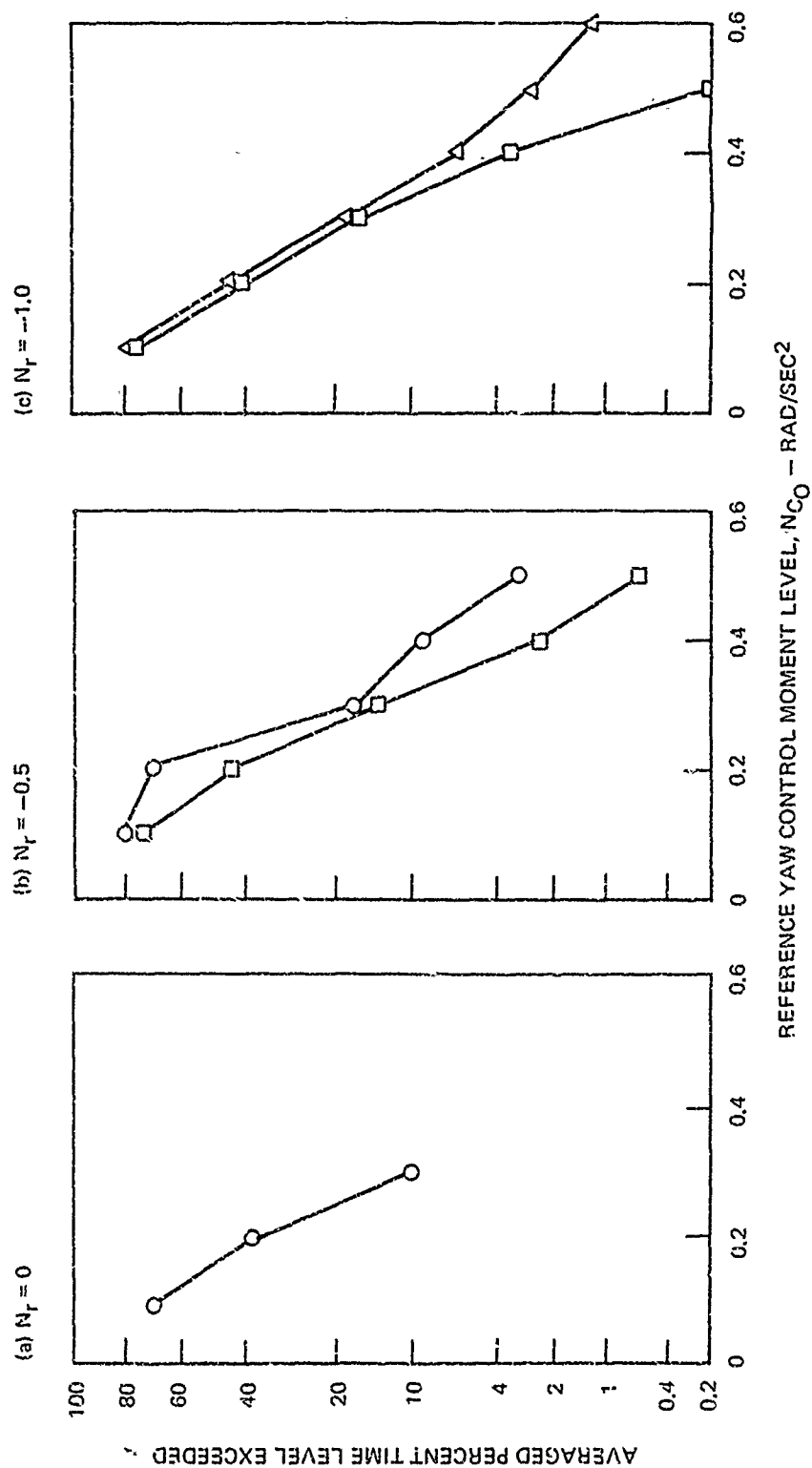


FIGURE E-10. Yaw Control-Moment Usage Exceedance Results

APPENDIX F

ADDITIONAL DETAILS OF THE UARL FLIGHT SIMULATION

This Appendix is a supplement to the description of the UARL flight simulation contained in this report (Section II.B). Details of the equations used to represent V/STOL aircraft motion in hovering and low-speed flight are discussed initially, here. The characteristics of the flight simulator controls are detailed next and the motion washout logic is described in the final section of this Appendix.

A. Equations of Motion

The general form of the six-degree-of-freedom perturbation equations of motion for V/STOL hovering and low-speed flight are given in Eq. (F-1).

$$\begin{aligned}
 M_u \dot{u} + M_\theta \dot{\theta} + M_q \dot{q} - \dot{q} &= -M_{\delta_e} \delta_e - M_u (u_g + U_m \cos\psi) \\
 L_v \dot{v} + L_\phi \dot{\phi} + L_p \dot{p} - \dot{p} &= -L_{\delta_a} \delta_a - L_v (v_g - U_m \sin\psi) \\
 N_v \dot{v} + N_r \dot{r} - \dot{r} &= -N_{\delta_r} \delta_r - N_v (v_g - U_m \sin\psi) \\
 X_u \dot{u} - q\dot{w} + r\dot{v} - \dot{g} (\sin\theta + \sin\gamma) - \dot{u} &= -X_u (u_g + U_m \cos\psi) - X_{\delta_e} \delta_e \\
 Y_v \dot{v} - r\dot{u} + p\dot{w} + \dot{g} \sin\phi \cos(\theta + \gamma) - \dot{v} &= -Y_v (v_g - U_m \sin\psi) - Y_{\delta_a} \delta_a \\
 Z_w \dot{w} - p\dot{v} + q\dot{u} + \dot{g} (1 - \cos\phi \cos\theta - \cos\psi \cos\gamma) - \dot{w} &= -Z_{\delta_c} \delta_c \\
 \dot{\gamma} &= 0.087 \text{ TS} \\
 \dot{\theta} &= q \cos\phi - r \sin\phi \\
 \dot{\phi} &= p + q \sin\phi \tan\theta + r \cos\phi \tan\theta \\
 \dot{\psi} &= (q \sin\phi + r \cos\phi) \sec\theta
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} X_u \dot{u} - q\dot{w} + r\dot{v} - \dot{g} (\sin\theta + \sin\gamma) - \dot{u} &= -X_u (u_g + U_m \cos\psi) - X_{\delta_e} \delta_e \\ Y_v \dot{v} - r\dot{u} + p\dot{w} + \dot{g} \sin\phi \cos(\theta + \gamma) - \dot{v} &= -Y_v (v_g - U_m \sin\psi) - Y_{\delta_a} \delta_a \\ Z_w \dot{w} - p\dot{v} + q\dot{u} + \dot{g} (1 - \cos\phi \cos\theta - \cos\psi \cos\gamma) - \dot{w} &= -Z_{\delta_c} \delta_c \end{aligned}} \right\} (F-1)$$

The various terms and symbols are described in the List of Symbols. The equations are for a body axis coordinate system and have been normalized with aircraft mass and moments of inertia. Stability derivatives on the left side of the equations describe the aerodynamic, propulsive and stability augmentation forces and moments. Terms on the right side describe the forces and moments induced by control inputs, the simulated turbulence and the mean wind. With the exception of N_v , the derivatives which couple motion between axes have generally been assumed to be negligible. However,

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pitch and roll rate coupling and control coupling were examined in one of the longitudinal and lateral control studies (Sections II.A.1.f. and III.A.5.). For this investigation the terms $M_{\dot{p}}$ and $L_{\dot{q}}$ were added to the left side of the pitch and roll moment equations, respectively, and the terms $M_{\delta_a} \delta_a$ and $L_{\delta_e} \delta_e$ were added to the right side of these respective equations. Also, it should be noted that the mean wind, U_m , was from 000 degrees true and it therefore affected the lateral and directional forces and moments, especially during the ± 180 deg turn subtask. Finally, the relationship for $\dot{\gamma}$ describes the rate-command, thumb-switch control characteristic for the thrust-vector angle, γ . The parameter TS was either 0 or 1 and, consequently, the pilot could command a 5 deg/sec rate-of-change of thrust-vector angle (or wing-tilt angle) to trim the effects of the mean wind acting on the aircraft longitudinal drag parameter. For the study of independent thrust-vector control the rate-of-change of thrust-vector angle was treated as a parameter (Section III.A.6.).

B. Characteristics of the Flight Simulator Controls

A conventional floor-mounted control stick (the cyclic pitch control stick of the S-61) was used for attitude control. It was used without a force gradient and the inherent friction present was negligible. The full longitudinal and lateral travels of the control stick were ± 6.63 in. and ± 6.50 in., respectively. For height control, a conventional, floor-mounted helicopter-type collective control with adjustable friction was used (7.5 in. total travel). The rudder pedals (± 3.2 in. total travel) for yaw control did not have a force gradient and the inherent friction was negligible. An on-off thumb-switch control was also used to command a fixed rate-of-change of thrust-vector angle (5 deg/sec). For the study of independent-thrust-vector control (Section III.A.6.) different commanded rates-of-change were considered. Also, for one part of that study the thumb switch was used to control pitch attitude and the cyclic stick controlled thrust-vector angle (Section III.A.6.).

C. Flight Simulator Motion Washout System

A schematic flow diagram for the motion washout interface between the simulated V/STOL aircraft motion (from the equations of motion implemented on an analog computer) and the commanded flight simulator motion is shown in Fig. F-1. This washout system insures that the flight simulator remains within its motion limits. The characteristics of the washout system have been tailored as much as possible to the frequency response features of the human vestibular system (Ref. 11). First-order roll-offs (20 dB/decade) are used to attenuate the low-frequency flight simulator attitude motion. This roll-off at low frequencies is similar to the frequency response of the attitude motion sensors in the vestibular system (the semi-circular canals). Second-order roll-offs are used for the translational motion.

Crossfeeds between low-frequency longitudinal and lateral accelerations and pitch and roll attitude, respectively, are used to simulate these accelerations with components of the earth's gravity vector. Because of this feature these low-frequency aircraft accelerations are also subtracted from the simulator translational motion commands. A more complete description of the washout system is contained in Ref. 11.

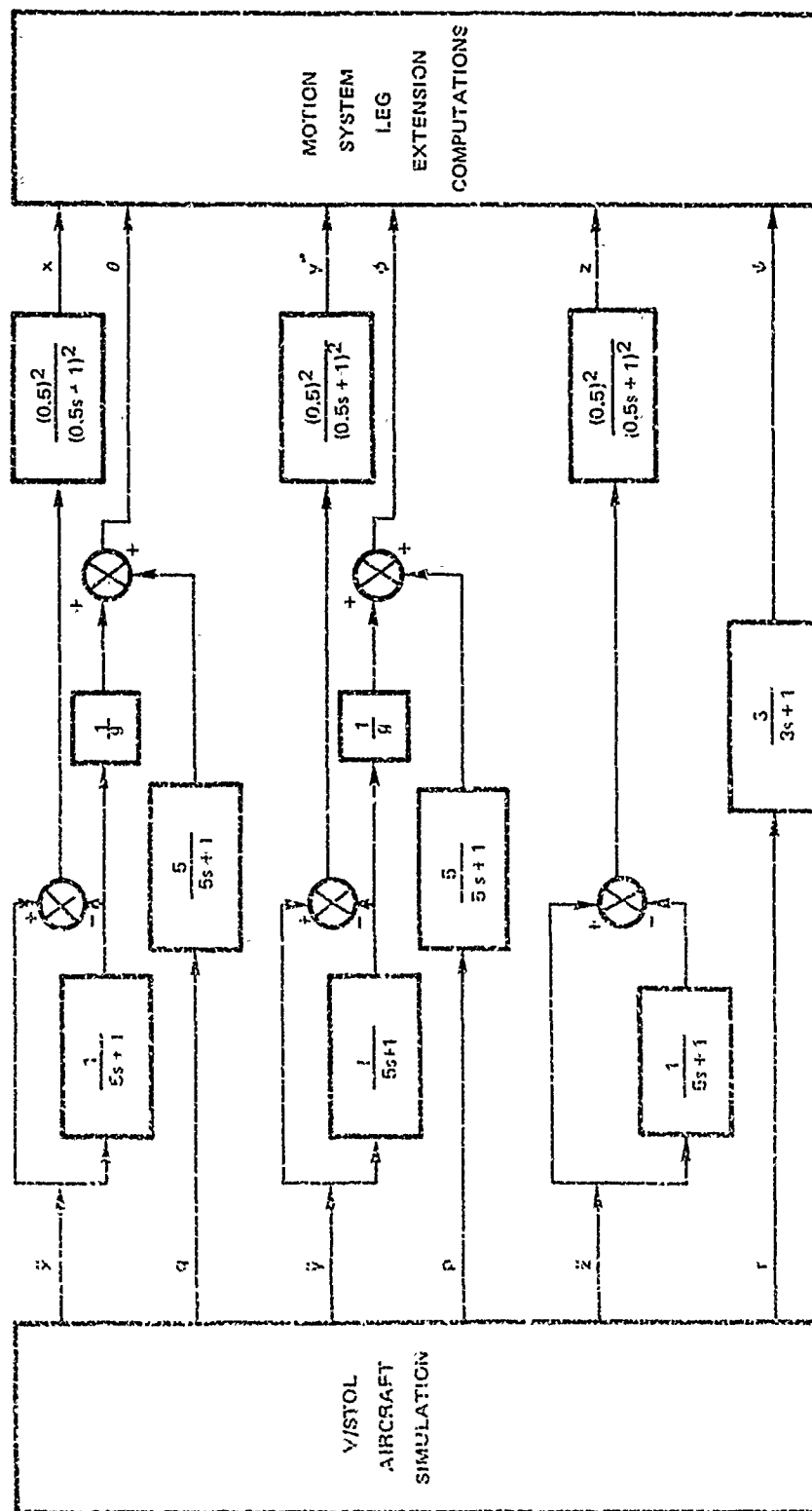


FIGURE F-1. Schematic Diagram of UAC V/STOL Flight Simulator Motion Washout System

REFERENCES

1. Anon.: MIL-F-83300-Military Specification-Flying Qualities of Piloted V/STOL Aircraft. July 1970.
2. Schaeffer, J., H. Alscher, G. Steinmetz and J. B. Sinscore: Control Power Usage for Typical Flight Maneuvering in Hover from a Systematic Analysis of Flight Test Data of the VJ101 Aircraft and of a Hover Rig. AIAA Paper No. 66-816, October 1966.
3. Schweizer, G. and H. Saelman: The Control Moment Distribution for the Do-31 Hovering Rig. AGARD Report No. 522, 1965.
4. Niessen, F. R.: Simultaneous Usage of Attitude Control for VTOL Maneuvering Determined by In-Flight Simulation. NASA TN D-5342, July 1969.
5. Kelly, J. R., J. F. Garren, Jr. and R. L. Deal: Flight Investigation of V/STOL Height-Control Requirements for Hovering and Low-Speed Flight Under Visual Conditions. NASA TN D-3977, May 1967.
6. Garren, J. F., Jr. and A. Assadourian: A VTOL Height-Control Requirement in Hovering as Determined From Motion Simulator Study. NASA TN D-1488, October 1962.
7. Vinje, E. W. and D. P. Miller: Analytical and Flight Simulator Studies to Develop Design Criteria for VTOL Aircraft Control Systems. AFFDL-TR-68-165, prepared by United Aircraft Research Laboratories, April 1969.
8. Miller, D. P. and E. W. Vinje: Fixed-Base Flight Simulator Studies of VTOL Aircraft Handling Qualities in Hovering and Low-Speed Flight. AFFDL-TR-67-152, prepared by United Aircraft Research Laboratories, January 1968.
9. McCormick, R. L.: VTOL Handling Qualities Criteria Study Through Moving-Base Simulation. AFFDL-TR-69-27, October 1969.
10. Clark, J. W. and D. P. Miller: Research on Factors Influencing Handling Qualities for Precision Hovering and Gun Platform Tasks. Proceedings of the Twenty-First Annual National Forum of the American Helicopter Society, May 1965.
11. Vinje, E. W. and D. P. Miller: A Motion Washout System for Rotational Moving-Base Simulators. United Aircraft Research Laboratories Report HL10606-1, November 1969.

REFERENCES (Cont'd)

12. Miller, D. P. and J. W. Clark: Research on VTOL Aircraft Handling Qualities Criteria. Journal of Aircraft, Vol. 2, No. 3, May 1965.
13. Clark, J. W. and D. P. Miller: Control Usage Data in Hover. United Aircraft Research Laboratories Unpublished Memorandum, June 1970.
14. Vinje, E. W.: An Analysis of Pilot Adaptation in a Simulated Multiloop VTOL Hovering Task. University of Michigan - NASA Conference on Manual Control, Ann Arbor, Michigan, April 1968. Also published in the IEEE Transactions on Man-Machine Systems, December 1968.
15. McRuer, D. T., D. Graham, E. S. Krendall and W. Reisener: Human Pilot Dynamics in Compensatory Systems. AFFDL-TR-65-16, July 1965.
16. Lollar, T. E. and G. K. L. Kriechbaum: VTOL Handling Qualities Criteria and Control Requirements - Analysis and Experiment. Journal of American Helicopter Society, Vol. 13, No. 3, July 1968.